Power Reduction of Hydrostatic Bearings for Grinding Machines

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Hydrostatic bearings used in the grinding wheel spindles of grinding machines have high stiffness and high damping against load fluctuation, as well as high rotating accuracy during grinding, however have larger power loss than other types of bearing. Therefore, the mechanism of power loss is elucidated using fluid analysis and a hydrostatic bearing with minimal power loss is developed. As a result, a developed bearing has reduced power loss by 24%.

Key Words: *hydrostatic bearing, grinding wheel spindle, power loss reduction, CFD*

1. Introduction

Hydrostatic bearings are bearings that support a spindle by the pressure of lubricant so that the spindle and bearing can maintain a constant state of non-contact. As a result, there is no wear or deterioration of the bearing components, and the life of the bearing is extremely long compared to other types of bearings. Moreover, the error averaging effect of the oil film can mitigate shape errors, roughness, and other anomalies of the spindle and bearing for achieving a rotational accuracy that is one order of magnitude more precise than the machining accuracy of these parts[1]. Also, the squeeze effect of the oil film provides a large damping force against dynamic external forces to ensure high dynamic rigidity.

At JTEKT, we have established a unique design theory for hydrostatic bearings and have developed the hydrostatic bearing with internal return flow shown in **Fig. 1**[2], a hydrostatic bearing with hydrodynamic effect[3], and a hydrostatic bearings with flow control system[4]. These technologies have enabled excellent accuracy and high productivity through grinding. However, in a grinding machine with a high peripheral velocity for attaining high productivity, the viscous resistance of the lubricant causes a large power loss. This paper presents our efforts to reduce the power loss in these hydrostatic bearings.

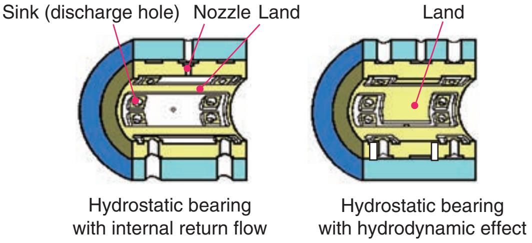

Fig. 1 JTEKT hydrostatic bearing technologies

2. Overview of Hydrostatic Bearings

2. 1 Principle of Hydrostatic Bearings

As shown in **Fig. 2**, hydrostatic bearings have a recess, which is a few millimeters deep, formed on the inner surface. The outer circumference of the recess has lands that hold the lubricant and typically form a clearance of 20 to 30 μm with the opposing spindle.

Lubricant pressurized by a pump passes through the restrictor and is supplied to each recess, and then flows out of the bearing through the clearance between the spindle and the land.During this process, the hydraulic force in the recess is determined by the outflow resistance of the restrictor and clearance, and this pressure supports the spindle. As shown in **Fig. 3**, by constructing the recesses with large cavity, the pressure drop in the bearing can be reduced, and a larger loading capacity can be obtained for a bearing of the same dimensions.

When an external force acts on the spindle and the clearance changes, the hydraulic force in the recess also changes to balance the external force. The relationship between this clearance and the hydraulic force is the stiffness of the hydrostatic bearing.

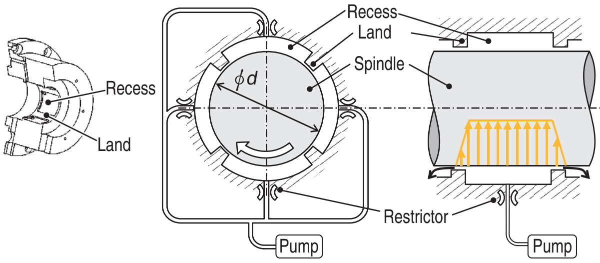

Fig. 2 Schematic drawing of hydrostatic bearing

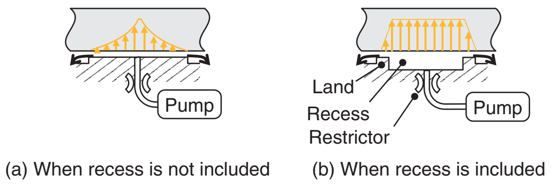

Fig. 3 Effect of recesses in hydrostatic bearing

2. 2 Power Loss in Hydrostatic Bearings

Because the entire loading surface of a hydrostatic bearing is in contact with lubricant, power loss due to viscous resistance occurs when the spindle rotates. The power loss can be approximated by Petrov's equation in Equation (1).

$$P=\pi \mu D^3 N^2 L/H \quad (1)$$

where,
P: Power loss
D: Bearing diameter
L: Bearing width
N: Rotational speed
H: Bearing clearance
μ: Coefficient of viscosity

From Equation (1), reducing the bearing diameter and width and increasing the bearing clearance are effective in reducing power loss. However, since these measures also reduce the stiffness of the bearing, they must be combined with measures to achieve higher stiffness. For example, there are hydrostatic bearings with hydrodynamic effect that use the wedge effect of rotation to generate hydraulic force in combination with the hydraulic force of hydrostatic bearings, and hydrostatic control systems that use flow control valves to optimally control the flow rate of lubricant according to the load for reducing the eccentricity of the spindle.

Similarly, in Equation (1), the power loss can be reduced by lowering the coefficient of viscosity of the lubricant, which has traditionally been addressed by using low-viscosity mineral oil. **Figure 4** compares the power loss during rotation when low-viscosity mineral oil and distilled water are used as lubricants in hydrostatic bearings. The specifications of the bearing are shown in **Table 1**. The coefficient of viscosity for distilled water is approximately 1/2 that of low-viscosity mineral oil, but the power loss was reduced by about 10%[5]. Consequently, technology must be developed that reduces the power loss regardless of the size of hydrostatic bearings and the coefficient of viscosity of the lubricant.

Table 1 Main dimensions of hydrostatic bearing

Specification		Value
Bearing diameter, mm		60
Bearing width, mm		50
Bearing clearance, mm		0.0175
Recess depth, mm		1
Bearing supply pressure, MPa		1.5
Rotational speed, min^{-1}		10 000
Coefficient of viscosity, mPa·s	Mineral oil	1.627
	Distilled water	0.890
Density, kg/m^3	Mineral oil	802
	Distilled water	997

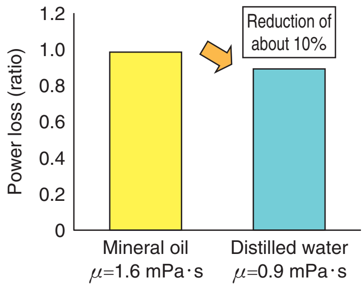

Fig. 4 Power loss with different lubricant

3. Reducing Power Loss in Hydrostatic Bearings

3. 1 Understanding the Causes of Power Loss in Conventional Hydrostatic Bearings

First of all, computational fluid dynamics (CFD) simulation of hydrostatic bearings was conducted to identify the area where power loss occurs in the hydrostatic bearing. The power losses are calculated from the two-dimensional models for the bearing recess and for the land, and the sum of the two values is used as the power loss of the entire bearing. A comparison of the fluid resistance of the land and recess at 10 000 min^{-1} is shown in **Fig. 5**. The vertical axis in **Fig. 5** is the shear stress acting on the spindle and shows the fluid resistance per unit area. The depth of the recess is several millimeters, which is about 50 times the bearing clearance of the land. Generally, the fluid resistance decreases in inverse proportion to the size of the clearance, but the fluid resistance of the recess is about the same as that of the land.

As indicated by the simulation of the flow in the recess shown in **Fig. 6**, the flow accompanying the spindle ("forward flow" below) occurs within about 1/3 of the recess depth, and the flow in the opposite direction to the rotation ("reverse flow" below) occurs in the remaining range. Due to the effect of this reverse flow, the forward flow does not have a gradual velocity change, but instead, it has a rapid velocity change near the spindle. Because the fluid resistance and power loss are proportional to the velocity gradient, a recess with a large clearance is considered to have a larger fluid resistance.

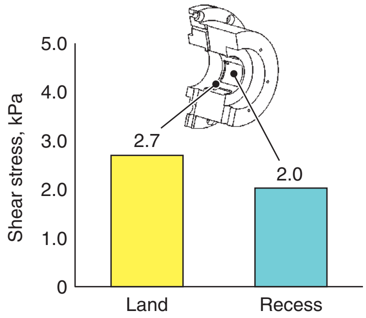

Fig. 5 Shear stress on land and recess

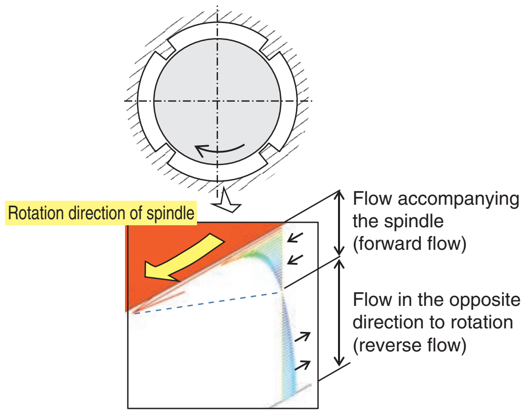

Fig. 6 Velocity vector plot in recess

For the shear stresses at the recess when the rotational speed of the spindle is varied from 50 to 10 000 min^{-1}, **Fig. 7** shows a comparison of the simulation results and the calculated values assuming laminar flow. The rotational speed on the horizontal axis and the shear stress on the vertical axis are both shown in logarithmic form. When the rotational speed reaches 350 min^{-1}, the solid line for the simulation results begins to deviate from the dashed line for the calculated value that assumes laminar flow, and it becomes about 10 times larger at 10 000 min^{-1}. This indicates that the power loss is affected by the turbulence.

As described above, it was found that both forward and reverse flows occurred at the recess, and their interference and turbulence caused a large power loss.

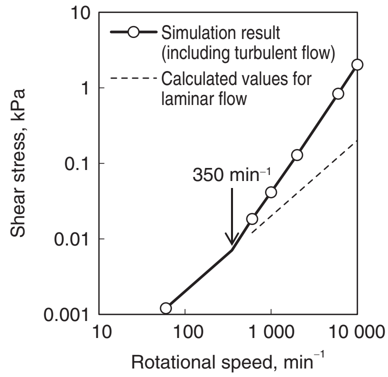

Fig. 7 Shear stress on recess

3. 2 Reducing Power Loss in Hydrostatic Bearings

The simulation up to the previous section showed that in order to reduce the power loss of hydrostatic bearings, it is effective to separate the reverse flow at the bottom of the recess so that it does not affect the forward flow. To achieve this, we devised a hydrostatic bearing with a separating plate inside the recess to separate the forward and reverse flows as shown in **Fig. 8**[6].

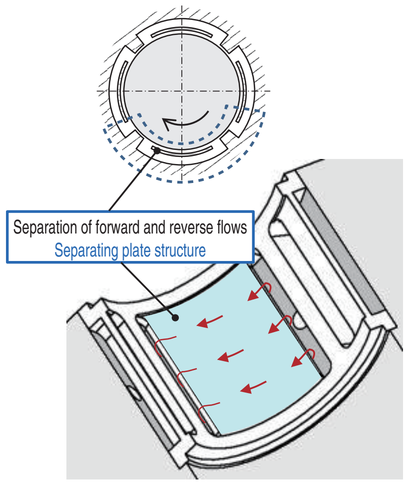

Fig. 8 Schematic of proposed hydrostatic bearing

To determine the position of the separating plate, the effect on the power loss of the size of the clearance between the plate and the spindle was simulated. The results are shown in **Fig. 9**. From this figure, we can see that there is a position for the separating plate where the power loss is minimized. Since the Reynolds number is small in the range where the distance between the spindle and the separating plate is small, the flow is laminar, and the viscous resistance is expected to decrease inversely proportional to the increase in the clearance. On the other hand, in the range where the distance between the spindle and the separating plate is large, the resistance due to turbulence and the pressure resistance due to the increase in forward flow rate are expected to increase.

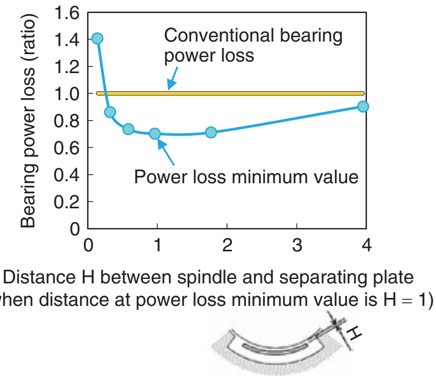

Fig. 9 Power loss by position of separating plate

Figure 10 shows the simulation results of the shear stress acting on the spindle surface under the conditions of minimum power loss in **Fig. 9**. For comparison, the simulation results of shear stress for conventional bearings are also shown. The horizontal axis of **Fig. 10** is the circumferential angle of the bearing. In the developed bearing with a separating plate inside the recess, the shear stress at the center separating plate is reduced by half compared to shear stress in a conventional bearing.

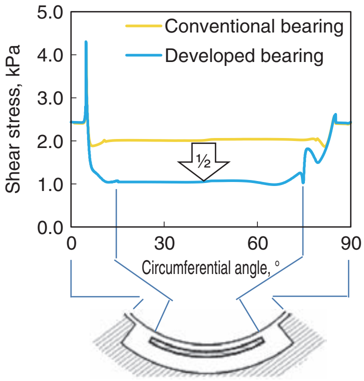

Fig. 10 Power loss reduction by separating plate

Based on the results of the above simulation, a new hydrostatic bearing was built as a prototype. The results of this power measurement are shown in **Fig. 11**. The power loss was measured using a torque meter by measuring the fluid resistance generated in the hydrostatic bearing. As shown in **Fig. 11**, the power loss of the developed bearing started to decrease around 3 000 min^{-1}, and at 10 000 min^{-1}, the power loss was reduced by about 34%.

The structure of the bearing with a separating plate described above is achieved by combining two parts. If we can Integrate two parts into one, we can reduce the manufacturing cost and improve the ease of assembly. Consequently, by applying the power loss reduction principles in this technology and using a single-component hydrostatic bearing, we were able to successfully reduce the power loss by 24%.

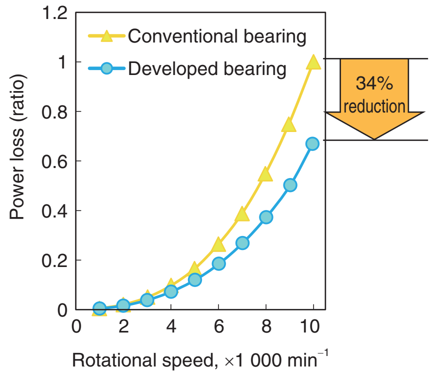

Fig. 11 Power loss of proposed hydrostatic bearing

3. 3 Verification Using a Grinding Wheel Spindle

This technology was installed on a grinding wheel spindle to evaluate the power loss. The evaluation bench is shown in **Fig. 12**. The grinding wheel spindle uses journal bearings primarily to support radial loads, such as the grinding force in the normal direction, and thrust bearings to support axial loads. Among these, the power loss of the grinding wheel spindle was compared with that of a journal bearing equipped with the developed bearing.

A comparison of the power loss of the grinding wheel spindle, the temperature rise of the lubricant, and the thermal displacement of the grinding wheel spindle is shown in **Fig. 13**. The power loss of the grinding wheel spindle was reduced by 13%, as shown in **Fig. 13**. The reduction in power loss for the grinding wheel spindle is smaller than a single bearing, but this is because power loss for the grinding wheel spindle includes the power loss of the thrust bearing, whose geometry is unchanged. The reduction in power loss also suppressed the temperature rise of the lubricant, which in turn reduced the amount of thermal displacement in the front-back direction of the grinding wheel head. Therefore, this technology reduces not only the power loss of the grinding wheel spindle, but also the power consumption of the oil cooler and the thermal displacement stabilization time.

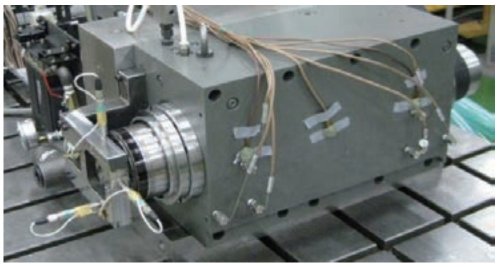

Fig. 12 Experimental apparatus of wheel head

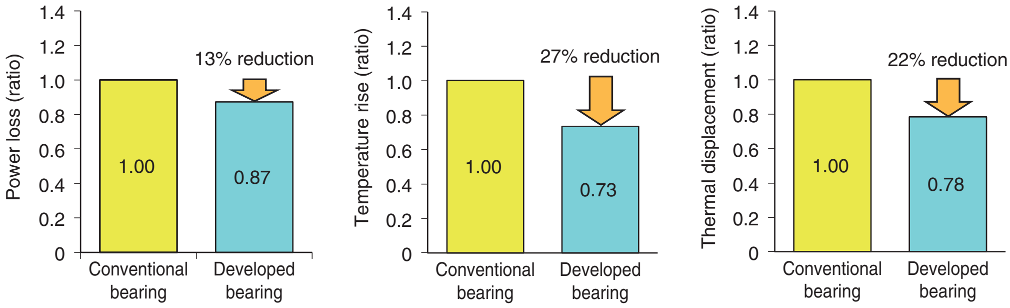

Fig. 13 Performances of existing hydrostatic bearing and proposed hydrostatic bearing

4. Conclusion

This paper presented a case study of power loss reduction by flow optimization of hydrostatic bearings. A camshaft grinding machine that used this technology received the 2020 Minister's Award for Excellent Energy-saving Equipment and Systems from the Ministry of Economy, Trade and Industry (METI). We will continue to improve the performance of our products and contribute to realizing carbon neutrality due to the ongoing need to reduce the power consumption of machine tools.

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