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Static characteristics of a water-lubricated hydrostatic thrust bearing with a porous land region and a capillary restrictor

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ABSTRACT

In this paper, a water-lubricated hydrostatic thrust bearing with a porous land region and capillary restrictor is proposed, and the results of theoretical and experimental investigations of its static characteristics are presented. The results showed that the water-lubricated hydrostatic thrust bearing with a porous land region had good operating characteristics; in particular, it had a high load capacity and static stiffness close to that of a porous bearing when operating with a clearance of less than 15 μm, and a high load capacity and static stiffness equivalent to that of a pocket bearing when running with a clearance larger than 15 μm.

1. Introduction

Aerostatic and oil-lubricated hydrostatic bearings have often been applied to various ultra-precision machining tools because of their ability of achieving high accuracy of motion of supported objects [1]. However, because of the low viscosity of air, it is difficult to suppress the generation of micro-vibrations [2]. Recently, the damping capability of aerostatic bearings became insufficient for achieving ultra-high machining accuracy. In the case of oil-lubricated hydrostatic bearings, environmental pollution became a very important issue. Thus, water-lubricated hydrostatic bearings have attracted considerable attention as a new component to enhance the precision of machine tools. This is because the viscosity of water is greater than that of air, and clean water does not pollute the environment.

The characteristics of water-lubricated hydrostatic bearings have been reported in a number of studies. A water-lubricated hydrostatic thrust bearing with a self-controlled restrictor for grinding machines has been studied [3], as have the static and dynamic characteristics of water-lubricated conical bearings with spiral grooves for a high-speed spindle, for improving load capacity and stiffness [4,5]. The static and dynamic characteristics of water-lubricated hydrostatic thrust bearings with a capillary, which are used in linear motion systems, have been investigated both theoretically and experimentally [6,7]. The static characteristics of water-lubricated hydrostatic bearings that use a constant-flow pump and that were developed for a linear motion system using a linear motor have also been studied [8,9]. Recently, water-lubricated hydrostatic porous bearings that have the advantage of being supplied with pressurized water from the entire area of the bearing surface have been receiving much attention. In a previous paper, Nishitani et al. investigated the characteristics of water-lubricated hydrostatic porous thrust bearings [10], and found that conventional bearings of this kind had a higher maximum load capacity than conventional water-lubricated pocket hydrostatic thrust bearings with a capillary restrictor, but lower maximum stiffness between the bearing clearance of 10 μm and 20 μm. Since water has lower viscosity compared with lubricating oil generally used for hydrostatic bearings, the suitable bearing clearance is thought to be around 15 μm, and a bearing structure suitable for such a small bearing clearance is required. Therefore, in this paper, a hydrostatic thrust bearing with a porous land region and a capillary restrictor that combines the advantages of both conventional hydrostatic porous and pocket thrust bearings is proposed, and the results of theoretical and experimental investigations of their static characteristics are presented.

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Nomenclature

dx, dy, dz	Grid width of a small control volume in x, y, z coordinates [m]
k_S	Bearing stiffness [N/µm]
k	Permeability of the porous material [m^2]
k_S	Bearing stiffness [N/µm]
K_S	Dimensionless bearing stiffness
h	Bearing clearance [µm]
l_{0x}	Outer width of the bearing in x direction [m]
l_{0y}	Outer width of the bearing in y direction [m]
l_{1x}	Pocket width of the bearing in x direction [m]
l_{2y}	Width of the bottom of steps of the porous material in y direction [m]
l_{1x}	Pocket width of the bearing in x direction [m]
l_{2y}	Width of the bottom of steps of the porous material in y direction [m]
p	Pressure [Pa]
p_a	Ambient pressure [Pa]
p_s	Supply pressure (absolute pressure) [Pa]
p_{sg}	Supply pressure (gauge pressure) [Pa]
p_i	Pressure at the inlet of a capillary [Pa]
p_o	Pressure at the outlet of a capillary [Pa]
t	Time [s]
t_0	Thickness of the porous material [m]
t_1	Height of the upper of step of the porous material [m]
t_2	Height of the bottom of step of the porous material [m]
t_p	Height of the pocket [m]
v	Water flow velocity [m/s]
v_x, v_y, v_z	Water flow speed in x, y, z coordinates [m/s]
d	Diameter of capillary [m]
l	Length of capillary [m]
C_D	Flow coefficient
Q	Volume flow rate [l/min]
W	Dimensionless load capacity
λ	Pocket ratio (= l_1/l_0)
μ	Viscosity of water [Pa.s]
ρ	Density of water [kg/m^3]

2. Bearing structure

The schematic views of the proposed bearing are shown in Fig. 1(a). The structure of the proposed bearing combines the conventional pocket bearing with a capillary restrictor and the porous bearing. Some of the pressurized water is supplied to the inner pocket through a capillary, and the remainder is supplied to the porous land region from the square feed groove with two holes of 3 mm in diameter that are formed on the bearing base plate.

The outer shape of the bearings was a square with a 24-mm side, and the porous land region, which was affixed on the bearing base plate, was t_0 = 4 mm thick. The pocket on the bearing was 19.2 mm wide (The pocket ratio, λ, i.e., the pocket length/bearing width, was 0.8). The side walls of the porous land region were sealed by forming end seals to prevent water from flowing out from the porous land region.

In this study, the proposed bearing, the conventional pocket bearing and the porous bearing are compared. Schematic views and the principal dimensions of the bearings are shown in Fig. 1(b), (c) and Table 1.

Table 1
Principal dimensions of the test bearings [mm].

	Proposed bearing	Conventional pocket bearing	Conventional porous bearing
$l_{0x} = l_{0y}$	24		
$l_{1x} = l_{1y}$	19.2		
$l_{2x} = l_{2y}$	12	–	–
t_0	4	–	3
t_p	–	2	–
t_1	2	–	-
t_2	2	–	–
d	0.4–0.8	0.4–0.8	–
l	5	5	–

3. Numerical calculation method

In the numerical calculation, water flow in the porous material was subjected to Darcy's law [11], shown by equation (1).

$$-\nabla p = \frac{\mu}{k} v,\ v = (v_x, v_y, v_z) \tag{1}$$

In the numerical calculation of the bearing characteristics, Darcy's law was used to describe the water flow through the porous land region, and the mass flow rates in a small control volume in the porous material (Fig. 2(a)) are given as follows:

$$\begin{aligned} mx|_{out} &= -\rho\frac{k}{\mu}\frac{\partial p}{\partial x}\Big|_{out} dydz, \quad mx|_{in} = -\rho\frac{k}{\mu}\frac{\partial p}{\partial x}\Big|_{in} dydz, \\ my|_{out} &= -\frac{k}{\mu}\frac{\partial p}{\partial y}\Big|_{out} dxdz, \quad my|_{in} = -\rho\frac{k}{\mu}\frac{\partial p}{\partial y}\Big|_{in} dxdz, \\ mz|_{out} &= -\rho\frac{k}{\mu}\frac{\partial p}{\partial z}\Big|_{out} dxdy, \quad mz|_{in} = -\rho\frac{k}{\mu}\frac{\partial p}{\partial z}\Big|_{in} dxdy. \end{aligned} \tag{2}$$

By assuming the continuity of the mass flow rate in a small control volume, the following equation was obtained.

$$mx|_{out} + my|_{out} + mz|_{out} - mx|_{in} - my|_{in} - mz|_{in} = 0. \tag{3}$$

In the calculations of pressure distribution in the bearing clearance, the mass flow rates in the x, y and z directions were expressed as follows:

$$\begin{aligned} mx|_{out} &= -\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial x} dy\Big|_{out}, \quad mx|_{in} = -\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial x} dy\Big|_{in}, \\ my|_{out} &= -\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial y} dx\Big|_{out}, \quad my|_{in} = -\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial y} dx\Big|_{in}, \\ mz|_{in} &= -\rho\frac{k}{\mu}\frac{\partial p}{\partial z}\mathrm{dxdy}. \end{aligned} \tag{4}$$

By assuming the continuity of the mass flow rate in a small control volume in the bearing clearance (Fig. 2(b)), the following equation was obtained.

$$\begin{aligned} & mx|_{out} + my|_{out} - mx|_{in} - my|_{in} - mz|_{in} \\ &= -\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial x} dy\Big|_{out} - \frac{\rho h^3}{12\mu}\frac{\partial p}{\partial y} dx\Big|_{out} \\ &+ \frac{\rho h^3}{12\mu}\frac{\partial p}{\partial x} dy\Big|_{in} + \frac{\rho h^3}{12\mu}\frac{\partial p}{\partial y} dx\Big|_{in} + \rho\frac{k}{\mu}\frac{\partial p}{\partial z} dxdy = 0. \end{aligned} \tag{5}$$

In this study, the following boundary conditions were assumed for the numerical solution of the derived equations.

At the outer wall of the porous material adjacent to the feed groove or feed pocket,

$$p = p_s,$$

at the bearing edge in the bearing clearance,

$$p = p_a,$$

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