Precision Engineering 41 (2015) 78–85

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

High performance hydrostatic bearing using a variable inherent restrictor with a thin metal plate

Hiroshi Sawano*, Yusuke Nakamura, Hayato Yoshioka, Hidenori Shinno

Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259-G2-19 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan

A R T I C L E   I N F O

Article history:
Received 6 August 2014
Received in revised form 8 February 2015
Accepted 16 February 2015
Available online 1 March 2015

Keywords:
Hydrostatic bearing
Variable inherent restrictor
High stiffness
Quick response
Load capacity
Flow rate

A B S T R A C T

Demands for machining of hard-to-cut materials have increased in a variety of industries. In order to meet such demands, high performance guideways are required for machine tools. In this study, in order to realize a bearing with high dynamic and static stiffness, a hydrostatic bearing using a variable inherent restrictor with a thin metal plate is newly proposed. The thin metal plate deforms elastically according to the pressure difference of working oil between both sides of the thin metal plate. Consequently, the deformation compensates the bearing clearance by adjusting the inherent restrictor. Modeling and numerical analysis of the proposed bearing were conducted, and the results confirmed that the bearing stiffness and response characteristics can be improved and then the oil flow can be reduced by applying the inherent restrictor with a thin metal plate. Furthermore, an experimental set-up for evaluating the bearing property was constructed and the load capability, static stiffness, dynamic stiffness, flow characteristic, and response characteristic of the bearing with the thin metal plate were compared with that of the bearing without the thin metal plate. The evaluation results of static performance confirmed that the flow rate of the bearing with the thin metal plate becomes lower as compared with that of the bearing without the thin metal plate, because the thin metal plate is acting as a fluid restrictor. In addition, the evaluation results of dynamic performance confirmed that the dynamic stiffness and the time response of the bearing were greatly improved by applying a variable inherent restrictor. These results confirmed that a high performance hydrostatic bearing can be realized by applying the proposed bearing.

1. Introduction

Hydrostatic bearing systems have been widely used in machine tools, because such bearing systems have high damping capacity and high stiffness. Demands for ultra-precision machining technology of hard-to-cut materials have recently increased. In order to meet such demands, high performance hydrostatic bearings are required to achieve machining of hard-to-cut materials.

There are many studies on improvement in the performance of a hydrostatic bearing. In order to improve the bearing performance, the methods for adding a membrane to a restrictor [1,2] and for changing the shape of a recess [3–5] have been proposed. In addition, the hydrostatic bearings with a variable external flow restrictor have been proposed as typical examples of the hydrostatic bearing with higher performance [6–9]. By using variable external flow restrictors, the static stiffness of a hydrostatic bearing can be improved significantly. However, such restrictors have a desirable problem which both dynamic stiffness and response decrease.

There are studies which improve the bearing performance by focusing on the working oil. Although oil is generally treated as incompressible fluid, air has actually compressibility. High bulk modulus fluid with quite low compressibility has been recently developed [10,11]. Kuze et al. proposed a hydrostatic bearing system with high stiffness using high bulk modulus fluid [12]. However, since working oil has the small effect on improvement in bearing performance, the hydrostatic bearing with a higher effect is required.

In order to realize the bearing with both high dynamic and static stiffness, this study proposes a novel hydrostatic bearing using an inherent restrictor with a thin metal plate. In addition, the static performance of the proposed bearing is theoretically analyzed. Furthermore, the performance evaluating experiments are also conducted to evaluate the proposed static and dynamic performance of the bearing.

* Corresponding author. Tel.: +81 45 924 5029; fax: +81 45 924 5029.
E-mail address: sawano@pi.titech.ac.jp (H. Sawano).

http://dx.doi.org/10.1016/j.precisioneng.2015.02.001
0141-6359/

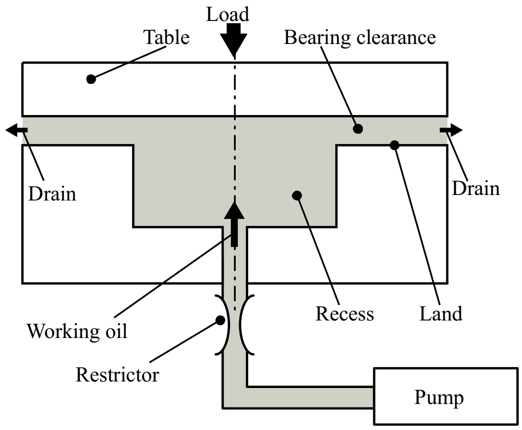

Fig. 1. Component of hydrostatic bearing.

2. Hydrostatic bearing using a variable inherent restrictor with a thin plate

Fig. 1 shows the typical structure of an example of a conventional hydrostatic bearing. Working oil is pressurized by a hydraulic pump and supplied to the bearing clearance through a fluid restrictor. A fluid restrictor has the function of pressure regulation which changes the pressure of working oil flowing in the recess according to the change in the bearing clearance due to the load. Static stiffness can be improved by making the fluid resistance of a restrictor higher. In addition, static stiffness can be further improved by controlling the flow of working oil so as to reduce the change in bearing clearance. However, because the working oil has small compressibility and there is a distance from a restrictor to a bearing, it takes time for the effect of regulation of the working oil flow in a restrictor to reach to a bearing and it causes the low response.

Fig. 2 shows a proposed hydrostatic bearing with a variable inherent restrictor. The proposed bearing has a thin metal plate nearby bearing surface. The plate deforms elastically according to the pressure difference of working oil between both sides of the plate. For example, when the load acting on the table increases, the proposed bearing behaves as described below:

(1) When the load increases, the table moves in the direction of the sinking. Consequently, the flow rate of working fluid reduces and then the pressure in the bearing clearance increases.
(2) With increasing the pressure in the bearing clearance, the deformation of the thin metal plate reduces. As a result, the function of the restrictor reduces and then the flow rate of working fluid increases.
(3) The table is pushed upward by increasing of the working fluid flow. Consequently, the displacement of the table caused by changing the load can be suppressed.

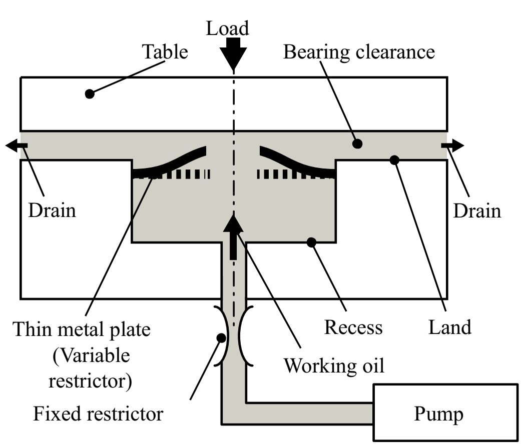

Fig. 2. Concept of a proposed hydrostatic bearing.

As mentioned above, the deformation compensates the bearing clearance by adjusting the inherent restrictor passively, and the static stiffness can be improved without any additional sensors and actuators. Thus, the proposed bearing has a similar structure of nozzle flapper mechanism. Furthermore, in the proposed bearing, because the inherent variable restrictor is put in the bearing clearance, the deformation of the plate arises in time to change of the bearing clearance, and change of the flow by deformation of the plate reaches to the bearing immediately. Therefore, the proposed bearing can realize a high response.

3. Theoretical analysis for evaluation of hydrostatic bearings

3.1. Bearing model for theoretical analysis

Theoretical analysis of the proposed hydrostatic bearing was conducted to evaluate the basic characteristics. Analytical model of the bearing with the thin metal plate is shown in Fig. 3.

The working oil pressured by a hydraulic pump with the pressure P_s is supplied to a fixed restrictor with the flow rate Q_1, and then sent to the recess with the pressure P_1 and the flow rate Q_2. When the working oil flows into the clearance between a thin plate and a levitating table from the recess, the pressure decreases from P_1 to P_2 by the effect of a variable inherent restrictor. In addition, when the working oil flows into the bearing clearance from the variable inherent restrictor with the flow rate Q_3, the pressure decreases from P_3 to P_4. The working oil flows out of the bearing clearance with the flow rate Q_4. The clearance between the inner edge of thin plate and the table h_{in} can be determined by the bearing clearance h_{land}, the step height of bearing surface and the thin plate h_1, and the deformation of the thin plate $z(r)$. In the theoretical analysis, following assumptions were carried out:

(1) Working fluid is the Newtonian fluid.
(2) Working fluid flow is steady and laminar.
(3) Inertial forces acting on the working fluid are negligibly small.
(4) The viscosity of the working fluid is a constant.
(5) No slip occurs between the working fluid and the bearing and the table surfaces.
(6) No moment load acts on the table.
(7) The table is kept stationary.

3.2. Theoretical analysis of the static characteristics of hydrostatic bearing

In the analytical model, the bearing pad is circularly symmetric. Reynolds equation which describes the state of working oil is expressed as follows.

$$\frac{1}{r} \cdot \frac{\partial}{\partial r} \left\{ rh(r)^3 \frac{\partial p}{\partial r} \right\} = 12\eta \cdot \frac{\partial h(r)}{\partial t} \qquad (1)$$

where η is the viscosity coefficient of the working oil. The left side of the equation expresses the pressure drop of the working oil due to the passage of a bearing clearance, and the right side of the equation expresses the squeeze effect. Since the clearance between the thin plate and the table $h(r)$ changes according to the distance from