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Externally pressurized gas journal bearing with slot restrictors arranged in the axial direction

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ABSTRACT

In this study, a novel rectangular slot restriction-type externally pressurized gas journal bearing was developed for use in high-speed rotating machinery, such as medical devices and industrial machines. The proposed bearing has several rectangular slot restrictors arranged in the inner surface of the bearing. To measure the bearing characteristics, a model was developed for the numerical calculation of the pressure distribution in the bearing clearance and the static characteristics of the bearing. The proposed bearing, which consists of two parts, was designed and can be manufactured using appropriate techniques. In this study, a prototype bearing with eight slots in its surface was manufactured as a test piece for fundamental tests. The diameter and length of the test bearing are 30 and 40 mm, respectively. The roundness of the bearing was measured using a three-dimensional coordinate measuring machine, and the results were used in the analysis. The pressure distribution and static characteristics obtained experimentally were found to be in good agreement with the calculated values. In the rotational tests, the rotor speed exceeded 380 Hz (22,800 rpm), and whirl vibration did not occur. During testing, the maximum rotor vibration amplitude was 0.002 mm, corresponding to an eccentricity ratio of 0.3.

1. Introduction

Externally pressurized gas journal bearings have advantages such as high-precision rotation, low frictional loss, and high rotational speeds. These bearings have been used in practical applications and have been studied for high-precision and high-speed devices, such as rotating machine tools and cryogenic turbo machines. Particularly, slot restrictors have been shown to produce a high load capacity and bearing stiffness [1]. Yoshimoto et al. have investigated and proposed a circular slot-restricted journal bearing and have numerically and experimentally clarified its static characteristics [2,3]. Park et al. have conducted stability analyses and experiments on a spindle system using nonuniform slot-restricted gas journal bearings [4]. Their results showed that this bearing is much more stable than a conventional slot-restricted bearing because of the nonuniform slot clearance. Sharma et al. have researched a slot restriction-type journal bearing for incompressible fluid [5,6]. They reported that asymmetric slot arrangements provide an improved stability threshold speed margin in comparison with asymmetric journal bearings. Ise et al. have researched the characteristics of a slot-restricted bearing with an asymmetric gas supply and an asymmetric bearing area and demonstrated that this bearing has a higher load capacity than conventional slot-restricted bearings [7–11].

The present authors have been developing new slot restrictor arrangement in a bearing that rotates at several tens of thousands of revolutions per minute with the aim of further performance improvement. In this study, the basic characteristics of the proposed bearing were verified as a first step in the development process. This report presents the calculation of static characteristics, an experimental verification of the pressure distribution and load capacity, and rotational test results. The results of this study demonstrate the sufficient practicality and effectiveness of the proposed bearing.

2. Configuration of the proposed bearing

The proposed bearing configuration is shown in Fig. 1(a) [12]. The bearing consists of two parts. To ensure the accuracy of the slot restrictor clearance after assembly, pins for positioning were

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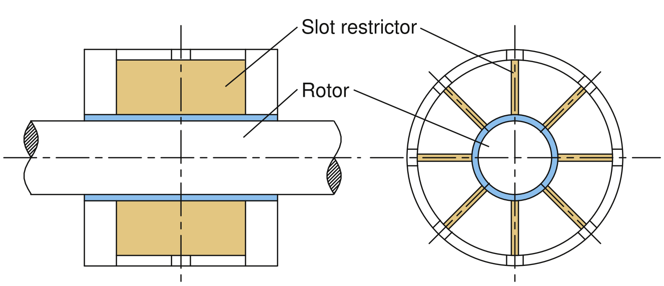
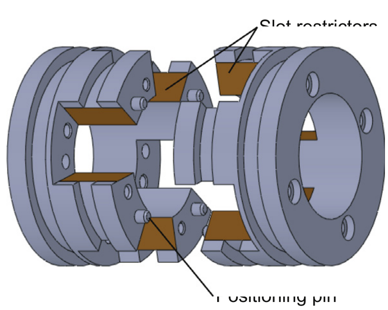
Nomenclature

B_{sl}	slot width
C_r	radial clearance
D	bearing diameter
F	force
h	clearance of an arbitrary segment
h_{sl}	slot clearance
L	bearing length
L_2	outflow length
L_{sl}	slot length
i, j	index of a segment in the developed surface
m, n	number of divisions
p	pressure in the bearing
p_s	supply gas pressure
q	mass flow rate of gas in a segment
Q	total gas flow rate
S	bearing surface area
W	load capacity
x, y	coordinates of the rotor vibration
ϵ	eccentricity ratio of the rotor in the bearing
θ	circumferential angle
ϕ	inclination angle
μ	viscosity coefficient of gas
ξ, ψ	coordinates for numerical calculation
$\Delta\xi, \Delta\psi$	segment length in the ξ- and ψ-directions

installed on the end faces of each part. Pressurized gas is supplied from an outer source to the gas channel in the outer ring of the bearing. Then, the gas flows to rectangular slot restrictors (orange areas in Fig. 1(a)). The restrictors have a very narrow clearance in the axial direction and are formed by the assembly of the parts. The gas flows into the atmosphere through the radial clearance of the bearing. In the configuration shown in Fig. 1(a), eight slots are set in the bearing. This configuration has the advantage of supplying a high gas pressure from several restrictors to the bearing surface.



(a) Cross section



(b) Outer view

Fig. 1. Configuration of the proposed slot journal bearing.

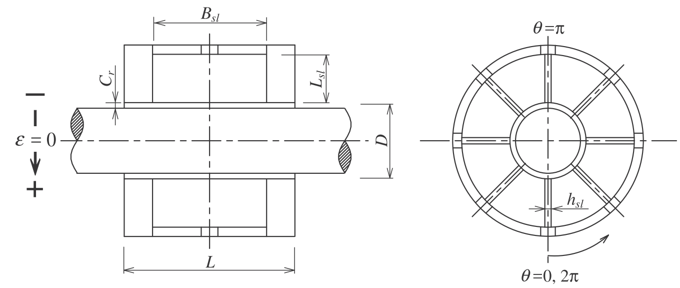


Fig. 2. Calculation model of the proposed bearing.

However, the number of restrictors in the final machined bearing can be changed by changing the practical conditions; this would greatly alter the characteristics of the bearing. The configuration of these restrictors can be expected to improve the angular stiffness. A prototype of the bearing for investigation in the present study was fabricated using polyacetal, which has excellent workability and tribological properties. When using a porous restrictor, high-pressure gas is supplied from the entire circumference of the bearing surface. However, the breathability of the material of the bearing affects its performance. From this point of view, the proposed bearing is considered useful.

3. Numerical calculation of the bearing characteristics

3.1. Calculation method

The calculation model for the proposed bearing is shown in Fig. 2. To calculate the static characteristics of the bearing, the divergence formulation method was applied [13–15]. In Fig. 2, the eccentricity ratio is defined such that positions below the geometrical center are positive. Moreover, the circumferential angle is defined as $\theta = 0$ at the bottom and increases with counterclockwise rotation. The supplied gas flows from the slot inlet to the bearing edge via the slot and bearing clearances. The developed surface is divided along the axial and circumferential directions (ξ- and ψ-directions, respectively) by integers m and n, respectively. Applying the continuity of flow principle to a small segment, as shown in Fig. 3, yields the following equation:

$$q_{\xi 2} - q_{\xi 1} + q_{\xi 4} - q_{\xi 3} + q_{\psi 3} - q_{\psi 1} + q_{\psi 4} - q_{\psi 2} = 0, \tag{1}$$

where $q_{\xi 1}$ and $q_{\psi 1}$ are defined as

$$q_{\xi 1} = \frac{1}{2}\frac{h^3_{i-1,j-1}}{24\mu}\frac{\Delta\psi}{\Delta\xi}\left(p^2_{i,j} - p^2_{i-1,j}\right), \; q_{\psi 1} = \frac{1}{2}\frac{h^3_{i-1,j-1}}{24\mu}\frac{\Delta\xi}{\Delta\psi}\left(p^2_{i,j} - p^2_{i,j-1}\right), \tag{2}$$

and $q_{\xi 2} \ldots q_{\xi 4}$ and $q_{\psi 2} \ldots q_{\psi 4}$ are can be expressed using the same form. Under eccentric conditions, the clearance $h_{i,j}$ is obtained as

$$h_{i,j} = C_r\left[1 - \epsilon\cos\left(\frac{\pi}{m}\right)\cdot i\right] \tag{3}$$

The load capacity W can be calculated by integrating the components along the loading direction of the gauge pressure in the bearing clearance over the bearing area, as

$$W = \int_S (p - p_a)\cos\theta \, dS. \tag{4}$$

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