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Comparative performance analysis of conical hydrostatic bearings compensated by variable slot and fixed slot

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ABSTRACT

Conical hydrostatic bearings with two different compensating devices have been proposed in this paper, which are classified as variable slot compensated hydrostatic bearing (VSHB) and fixed slot compensated hydrostatic bearing (FSHB), respectively. The mathematical models for them have been built with perturbation theory and solved by finite element method (FEM). Static loading experiment has been carried out to validate the research methodology. Then the static and dynamic characteristics of the proposed bearings have been comparatively studied. Results show that the VSHB exhibits a better radial performance of load carrying capacity and stiffness, but a worse radial damping performance, compared with FSHB under the same geometric and operational conditions.

1. Introduction

Conical hydrostatic bearings have been successfully used in various engineering applications, such as precision machine tools, for the advantage of being capable of carrying both axial and radial load. They have been widely and deeply studied in available literature. Prabhu and Ganesan [1] and Chandra et al. [2] studied multirecess conical hydrostatic thrust bearings theoretically taking into account the effect of rotational lubricant inertia. Nowak and Wierzcholski [3] analytically solved the non-Newtonian lubrication problem for conical journal bearing of finite width. Then Abdel-Rahman [4] analytically studied the non-isothermal flow of non-Newtonian lubricant through the gap of a conical bearing when an external magnetic field was applied on the basis of Nowak and Wierzcholski's work. Khalil et al. [5] theoretically investigated the effect of turbulent lubrication on the performance of externally pressurized conical thrust bearings with an algebraic Reynolds stress model and revealed that the turbulent flow solution gave higher dimensionless pressure, load and torque than the laminar flow solution. Yoshimoto et al. [6,7] studied two types of water lubricated hydrostatic conical bearings with spiral grooves by numerical and experimental methods, and found that the compliant surface bearing had a larger load capacity in a relatively large bearing clearance than the rigid surface bearing, and the proposed bearings were very stable at high speed. Sinha et al. [8] analyzed the thermal effect on a porous constant gap conical hydrostatic bearing under rotation and found the load capacity was reduced by the highly porous surface. Yang and Jeng [9] also analyzed the thermal effect on conical–cylindrical bearing performance and revealed that pressure increased both film viscosity and temperature. Abdel-Rahman [10] built a theoretical model of flow in a thin film between immobile conical surfaces, with quantity, location and dimensions of the feeders taken into account. Guo et al. [11] presented a theoretical and experimental study to recognize the dynamic performance of a hydrostatic deep/shallow pocket hybrid conical bearing compensated by flat capillary restrictors, which exhibited an advantage of high load capacity and high stability under small eccentricity. Sharma et al. [12] theoretically studied the influence of cone angle on the performance of four-pocket conical hydrostatic journal bearing system and concluded that the lubricant flow rate of conical journal bearing was significantly reduced vis-a-vis the corresponding similar circular hydrostatic journal bearing. They also studied the influence of wear on the performance of multirecess conical bearing and found that the direct fluid film stiffness coefficients, damping coefficients and stability threshold speed margin reduced as the bearing was worn [13]. Sharma and Rajput [14] revealed that micropolar lubricant offers better performance than Newtonian lubricant through theoretical study of conical hydrostatic bearings with different conical angle. Most studies reported in literature treat the conical bearing as either a thrust bearing or a journal bearing, although it can be both.

For a hydrostatic bearing, restrictors or compensating devices are basic elements to regulate the fluid flow into the recess so that it can maintain a fluid film force carrying external load. Restrictors may become the most effective impacting factor on the bearing performance if the hydrostatic bearing is used under low speed condition. Hydrostatic bearings with diversity of restrictors have been widely

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Nomenclature

C	Bearing clearance, mm
C_{ij}	Damping coefficients, N s/mm
C_r	Restricting coefficient of slot
F_x F_y F_z	Fluid film forces, N
G_m	The right item of the finite element equation
K	Fluidity matrix
N_i	Shape function in finite element
Q	Fluid flow rate, mm^3/s
R_a	Average radius of the bearing, mm
Sij	Stiffness coefficients, N/mm
W_a	Axial load, N
W_r	Radial load, N
h	Fluid film thickness, mm
h_0	Initial fluid film thickness, mm
h_r	Restricting fluid film thickness, mm
n	Recess number
p	Fluid pressure, Pa
p_s	Supply pressure, Pa
p_k	Pocket pressure, Pa
r	Axial coordinate
r_a	Average radius of developed bearing surface, mm
r_i	Inner radius of developed bearing surface, mm
r_o	Outer radius of developed bearing surface, mm
t	Time, s
α	Semi-conical angle
β	Concentric restricting ratio
δ_y	Radial displacement, mm
δ_x	Axial displacement, mm
φ	Circumferential coordinate
η	Local horizontal coordinate in an element
η_i	Local horizontal coordinate at Node i of an element
μ_s	Reference dynamic viscosity, N s/m^2
ω	Rotation speed, rad/s
ξ	Local vertical coordinate in an element
ξ_i	Local vertical coordinate of Node i of an element
$\Delta\dot{x}$,$\Delta\dot{y}$, $\Delta\dot{z}$	Velocity disturbances, mm/s

Non-dimensional parameters

$\overline{C}_{ij}$	$C_{ij}(C^3/\mu_s R_a^4)$
$\overline{F}_x$, $\overline{F}_y$, $\overline{F}_z$	$F_x/(p_s R_a^2)$,$F_y/(p_s R_a^2)$,$F_z/(p_s R_a^2)$
$\overline{Q}$	$Q(\mu_s/p_s C^3)$
$\overline{S}_{ij}$	$S_{ij}(C/\mu_s R_a^2)$
$\overline{W}_a$	$W_a/(p_s R_a^2)$
$\overline{W}_r$	$W_r/(p_s R_a^2)$
$\overline{h}$	h/C
$\overline{p}$	p/p_s
$\overline{p}_k$	p_k/p_s
$\overline{r}$	r/r_a
$\overline{t}$	$t(\mu_s R_a^2/C^2 p_s)$
$\overline{\mu}$	μ/μ_s
ε	δ_y/C
ζ	δ_z/C
$\overline{\varpi}$	$\omega(\mu_s R_a^2/C^2 p_s)$
$\Delta\overline{x}\Delta\overline{y}\Delta\overline{z}$	$\Delta x/C$,$\Delta y/C$,$\Delta z/C$
$\Delta\dot{\overline{x}}$	$\Delta\dot{\overline{y}}\Delta\dot{\overline{z}}\Delta\dot{x}/(\mu_s R_a^2/Cp_s)$,$\Delta\dot{y}/(\mu_s R_A^2/Cp_s)$,$\Delta\dot{z}/(\mu_s R_a^2/Cp_s)$

Subscripts

0	initial
a	axial or average
k	pocket
r	radial or restricting
s	supply

studied [15–19]. Slot restrictor is one of the commonly used restrictors. Sharma et al. [20] studied the slot-entry hydrostatic/hybrid journal bearing using finite element method and revealed that asymmetric slot-entry journal bearings provided an improved stability threshold speed margin compared with those compensated by capillary, orifice and constant flow valve restrictors. Elastic effect, thermal effect and non-Newtonian lubricant effect were found having a great influence on the performance of slot-entry journal bearings [21–23]. Garg et al. [24,25] theoretically investigate the performance of slot-entry hybrid journal bearings considering combined influences of thermal effects and non-Newtonian lubricant, and compared the results with hole-entry bearing. Results indicate the direct stiffness coefficients, damping coefficients and stability parameters of slot-entry bearing are not as good as hole-entry bearing under the given operation and geometry parameters. Sharma et al. [26] pointed out that the slot-entry hybrid journal bearing operating with micropolar lubricant had an increase of minimum fluid film thickness and a reduction of friction coefficient as compared with corresponding similar slot-entry bearing operating with Newtonian lubricant. Generally slot restrictor is a fixed one, whose restriction parameters do not change. Kane et al. [27] proposed a so-called self-compensating hydrostatic bearing, and its restrictor is essentially a slot formed by the rotor part and the stator part, which can change when the rotor moves in the radial direction.

In this paper, conical hydrostatic rotary bearings with two types of compensating slot have been comparatively studied. The bearings compensated by fixed slot are named fixed-slot compensated hydrostatic bearing (FSHB), and the others which are compensated by variable slot are named variable-slot compensated hydrostatic bearing (VSHB). Perturbation method was applied to model the bearings and finite element method (FEM) was used to calculate the static and dynamic characteristics. The influence of conical angle on the bearing performance has been studied. Both the performances in the axial and the radial directions have been discussed and the influence of the variable slot has been investigated.

2. Bearing structures and test rigs

The typical proposed conical hydrostatic rotary bearings are diagramed in Fig. 1. The first type is VSHB, compensated by variable slot which is formed by an inner stator surface and a rotor surface. The restricting slot is essentially an inner clearance, which changes when the rotor is displaced in the radial direction. The second type is FSHB, compensated by fixed slot which is formed by the outer stator surface and the bushing. Both the two types of bearings have restrictor units to regulate the flow into the pockets. A restrictor unit is an independent region demarcated by grooves on the restricting surface. It connects to a pocket via internal passage. The fluid pressure decreases when it flows across the restrictor unit, and the pocket pressure is defined by the flow resistance ratio of the restrictor unit to the bearing land. When the rotor is displaced, this flow resistance ratio changes to regulate the pocket pressure, thus restoring fluid film force is generated to exhibit stiffness. For FSHB the restricting slot is fixed, so its resistance to the lubricant flow keeps constant, thus the fluid pressure in the bearing is defined only by the variation of the