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Theoretical investigation on porous tilting pad bearings considering tilting pad motion and porous material restriction

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ABSTRACT

Porous tilting pad bearings (PTPBs) hold potential for applications that require high bearing stiffness and good stability. This study presents a numerical analysis of PTPBs. A three-dimensional Darcy's equation is coupling solved with the motion equation of tilting pads to establish the air pressure field among the porous materials and gas film. The static performance solved by finite difference method and the dynamic characteristics obtained from perturbation equations are presented for various design parameters, such as bearing clearance, supply pressure, tilting, and radial stiffness. Predictions generally agree with the published load capacity. The coupling mechanism of hydrostatic and hydrodynamic effects in gas film are investigated. The predictions show that PTPB performance is determined by externally pressurized gas and shaft rotation.

1. Introduction

Aerostatic bearings, which offer low friction and possess high rotary precision, have been widely used in high-speed rotating machinery and ultra-precision measuring instruments [1–5]. Porous material surface controls gas flow rates and serves as a type restrictor in externally pressurized porous gas bearings. In comparison with conventional-type restrictors, such as pocketed orifices, annular orifices, and slot channel, porous bearings ensure equal distribution of pressured gas in bearing clearance and result in the advantages of higher load capacity, better damping, and higher stiffness with a similar mass flow rate [6–10]. A new type of porous gas bearing – porous tilting pad bearing (PTPB) – has recently been presented and drawn much attention due to its high load capacity, low power loss, operation potential at high rotational speeds, and high stability [11–15]. This type of porous gas bearing has been successfully used in various applications, such as miniature turbomachinery and production machine tool component [11,12].

Porous gas bearings have been extensively studied theoretically and experimentally by many researchers [16]. In 1955, Montgomery and Stetty [17] first successfully rotated a shaft at a speed of 25 krpm supported by a porous journal bearing and showed the possibility of porous wall gas bearing in high-speed application. Sneck et al. [18–20] investigated the performance of porous gas bearings by presenting a modified Reynolds equation, which only considered a radial gas flow in porous materials, to simulate the performance of a porous journal bearing; the authors analyzed the beneficial effect of shaft rotation on load capacity. Mori et al. [21,22] considered the circumferential and radial gas flow in the bearing film and porous materials by comparing the theoretical models in Refs. [18–20]. The authors used the equivalent clearance model to analyze the static performance of the bearings and found that the bearings had excellent static characteristics. Mori and Yabe [23] then proposed an improved numerical model for describing the three components of air flow in porous materials. The air flow in axial and circumferential flows in porous materials was assumed to flow in equivalent clearance, and the radial flow was supposed to flow in capillary.

Moreover, Majumdar [7,24] provided a modified Reynolds equation considering three-dimensional gas flow in porous materials. For further research on stiffness calculations of bearings, they analyzed the bearings with rotation and the effect of shaft oscillation on the bearings. The effect of bushing thickness, supply pressure, and feeding parameter on the stability characteristics of porous journal bearings was investigated [25]. Pal and Majumdar [26] analyzed the dynamic behavior of porous journal bearings based on the modified Reynolds equation. Gargiulo [27,28] theoretically and experimentally investigated the dynamic characteristics of porous journal bearings and showed that supply pressure, speed, and bearing clearance might influence the dynamic stiffness and damping coefficients. Otsu et al. [29] proposed a theoretical model using three-dimensional Darcy's equation in porous materials to analyze the static and dynamic characteristics of aerostatic porous journal bearings and found the influence of the permeability of porous materials on the dynamic stiffness and damping coefficient. Ana

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Nomenclature

Symbol	Description
W	Pad width (m)
L	Pad axial length (m)
H_1, H_2, H_3	Height of base plate, height of pad and height of groove (m)
r_0, r_d	Pad radius and shaft diameter (m)
Θ_p	Pad arc angle (rad)
θ_s, θ_e	Pad leading edge and pad trailing edge (rad)
θ_p	Angular position of pivot (rad)
δ, ξ	Pad radial displacement (m) and pad tilting angle (rad)
m_p, I_p	Pad mass (kg) and moment of inertia of pad (kg·m^2)
p_a, p_s	Ambient and supply pressures (pa)
p	Pressure (pa)
P	Dimensionless pressure (p/p_a)
r, θ, z	Coordinates in the r, θ, and z directions
R, Z	Dimensionless coordinates in the r and z directions
C	Nominal clearance (m)
h, H	Film thickness (m) and dimensionless film thickness (h/C)
e_x, e_y	Components of rotor eccentricity
ω	Angular velocity of shaft (rad/s)
m_θ, m_r, m_z	Mass flow rate in the θ, r and z directions
Δm_t	Varied amount of mass flow rate per unit time
W_0	Dimensionless load capacity
Q	Dimensionless mass flow rate of the bearing
x, y	X and y axes
F_x, F_y	Forces acting on shaft along the x and y axes caused by gas pressure (N)
F_{px}, F_{py}	Forces acting on pad along the x and y axes caused by gas pressure (N)
$F_{p\delta}$, $M_{p\xi}$	Radial force (N) and tilting moment (N·m) acting on the pad caused by gas pressure
K_δ	Radial stiffness of the straight beam (N/m)
K_ξ	Tilting stiffness of the pivot (N·m/rad)
Δx, Δy	Shaft perturbation amplitude along x and y axes (m)
$\Delta\delta$, $\Delta\xi$	Pad perturbation amplitude along radial (m) and tilting (rad) direction
υ	Excitation frequency (rad/s)
η	Porosity of porous materials
k	Permeability of porous materials (m^2)
H_p	Thickness of porous block (m)
μ, ρ	Gas viscosity (Pa·s) and density (kg/m^3)
$\mathfrak{R}$	Air gas constant (J/kg·K)
T	Temperature of the supply gas (K)

M. Balasoiu et al. [30] studied the parametric of a porous self-circulating hydrodynamic bearing. However, the abovementioned studies have mainly focused on porous wall gas bearings that only have one circular porous materials as the bearing surface. This type of fixed-geometry bearing has inherent limitations on stability.

By contrast, tilting pad gas bearings are well-known for their inherent stability [31]. The pads can move following the rotor movements to adjust their position; thus, the cross-coupling stiffness of tilting pad bearing is low. San Andrés [32] built a computational model of flexure-pivot hybrid bearings that combined the hydrostatic and hydrodynamic effects. Predictions of the bearings demonstrated that they could be used in high-speed applications that require good stability. Hybrid flexure-pivot tilting pad gas bearings were also analyzed and experimented to validate whether they were suitable for high-speed micro turbomachinery because of their enhanced stability characteristics [33]. Feng et al. [34] analyzed flexure-pivot tilting pad gas bearings with metal mesh dampers. The flexure-pivot tilting pad gas bearing model and the metal mesh model were integrated into a new bearing model to predict the static and dynamic performances of the bearings. The metal mesh was introduced into the flexure-pivot tilting pad gas bearing and improved the direct stiffness and damping coefficients of the bearing. Andrea Rindi et al. [35,36] developed a three-dimensional models of tilting pad journal bearings that considers the rotor dynamics and the lubricant supply plant and the models has been validated by experiment.

However, research on PTPBs is limited. Heller and Shapiro [11] tested this type of porous hydrostatic gas bearing for miniature cryogenic turbomachinery. In the test, a three-pad porous hydrostatic bearing mounted to a cartridge by a novel spring showed an excellent performance in power loss, gas flow rate, and load capacity. The experimental results showed that the three-pad porous bearing performed well in miniature turbomachinery applications and was suitable for high-speed applications. San Andrés et al. [12] analyzed the performance of five-pad porous journal bearings in terms of drag torque, gas flow rate, and rotor dynamic response. PTPBs had many degrees of freedom and air flow in porous materials. Their analysis required to assume a number of pad motion and air flow. Consequently, no complete theoretical system was available to study the performance of the bearings.

This study presents a numerical model for porous tilting pad gas bearings considering the structural effect of the tilting pad and porous material restrictor. A three-dimensional Darcy's equation is coupling solved with the motion equation of tilting pads to establish the air pressure field among the porous materials and gas film. The static performance solved by finite difference method and the dynamic characteristics obtained from perturbation equations are presented for various design parameters, such as bearing clearance, supply pressure, radial stiffness, and tilting stiffness. This work also shows the effectiveness of the hydrostatic and hydrodynamic effects of the bearings. This study has guiding significance in determining PTPB parameters.

2. Description of PTPBs

Figure 1 shows the schematic of a shaft and a PTPB. A PTPB contains several arched porous pads (five in this study), and each arched porous pad connects to the bearing pedestal by a threaded stem. The threaded stem goes through the hole on inner wall of the bearing pedestal and supports the pad by a threaded stem to allow the pad to tilt freely along the axial and circumferential directions, as shown in Fig. 2. Two nuts and two Belleville springs that pass through the threaded stem are used to adjust the mechanical pretightening force. The gas film is determined by the combined action of the pretightening force and the supply pressure.

An arched porous pad consists of a base plate and a porous block that is securely mounted on the base plate with adhesive, as shown in Fig. 2. The pressurized air, which is provided by the supply orifice, flows into the air supply grooves in the base plate and finally flows into the bearing

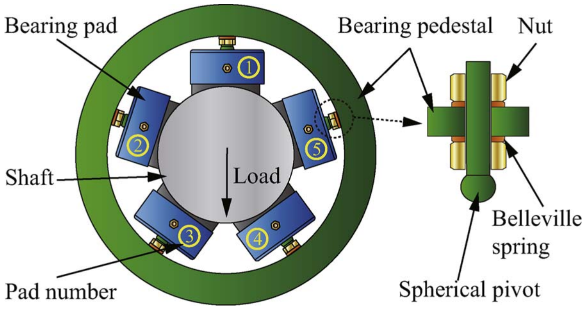

Fig. 1. Schematic of a PTPB.