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Performance and stability analysis of gas-lubricated journal bearings in MEMS

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ABSTRACT

A mathematical model and a computational methodology are presented to simulate the complicated flow behaviors of the journal microbearing in the slip regime, at which the Knudsen number ranges from 0.01 to 0.06. A modified Reynolds equation is derived with the slip effect. Static performances of the microbearing are analyzed using spectral collocation method. The effects of the length-to-diameter ratio and slip on the stability of the system are analyzed and the corresponding stability boundaries are calculated numerically. The results indicate that the slip-flow boundary condition enhances the stability of the equilibrium points of the gas-lubricated journal bearing-rotor system.

1. Introduction

Gas-lubricated bearings are used in high-speed rotating machinery to take advantage of their characteristics of low friction loss, low noise, minimal temperature limitation and maintenance needs. With the intense interest of high-power-density micro-electro-mechanical systems (MEMS), the stable high-speed operation of the gas-lubricated microbearings becomes one of the serious challenges in pursuit of this development Ehrich and Jacobson [1] designed an experimental high-speed gas-lubricated high-power-density micro-turbine. Isomura et al. [2] designed and fabricated a high-speed microbearing test rig to continue development of air bearings for a micro-gas turbine that is capable of operating stably at 870,000 rpm. Kim et al [3] designed and fabricated gas microbearings with deep X-ray lithography and electroplating and calculated the performances of microbearings in terms of load parameters and attitude angles using Molecular Gas Lubrication (MGL) theory. These studies share the common feature that the radial clearance ratio of the micro-journal bearing is relatively large while the operating bearing eccentricity ratio would be about 0.9 in order to maintain stability, consequently molecular effects are not negligible and stability consideration must be concurrent with a high operating eccentricity.

Traditionally, the classical Reynolds equation had been applied to analyze and model gas-lubricated journal microbearings. Piekos and Breuer [4] studied the stability of a hydrodynamic journal bearing in a micro-gas turbine using pseudo-spectral orbit simulation. The results indicated that the Reynolds equation is suitable for the analysis of gas-lubricated journal microbearing. Orr [5] applied a macro-scale model to investigate the characteristics of a gas-lubricated journal bearing in a micro-gas turbine and found that there was not only whirl but also radial instability in extremely short gas bearings. Zhang and Shan [6] investigated the dynamic performance of gas microbearings in microsystems and found that the load carrying capacity of the journal bearing with low aspect ratio is linearly proportional to its bearing number. A low-order rotordynamic model for hydrodynamic microbearings was reported in [7], which employed stiffness and damping coefficients predicted by other high-order numerical models. The results demonstrated that the microbearings should operate at a hybrid mode where the bearing relies on hydrostatics at low speeds and hydrodynamics at high speeds. Spakovszky and Liu [8] firstly derived the scaling laws for the dynamics of ultra-short hydrostatic gas-lubricated journal bearings. Liu et al. [9] presented a new analytical model, which contains a fluid dynamic model for axial flow gas-lubricated journal bearings and a rotordynamic model for microbearings, for axial flow micro gas-lubricated journal bearings. In addition, Boedo and Booker [10] proposed a novel finite element elastohydrodynamic (EHD) lubrication analysis appropriate for gas-lubricated journal bearings using dynamic conditions.

Slip effects are significant for gas flows in close spacing and appropriate corrections to the Reynolds equation are necessary. The level of rarefaction effect could be represented by the Knudsen number Kn, defined as the ratio of the molecular mean free path λ to the minimum spacing h. A wide range of Knudsen numbers is possible in gas-lubricated microbearings, but the slip flow regime with $10^{-3} < Kn < 0.1$ is the most frequent. For gas-lubricated journal microbearings used in micro-rotating machinery, the eccentricity ratio of them often varies from 0.5 to 0.9, the local Knudsen number

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Nomenclature

a	accommodation coefficient
e	eccentricity
h	film thickness
i,j	integral numbers
$kron(\bullet)$	Kronecker product
p	pressure
p_a	ambient pressure
t	time
$\mathbf{D}_{ab}$	Kronecker product matrix
F_g	total bearing force
$F_{gr},F_{g\theta}$	bearing forces in the radial and tangential directions
H	dimensional film thickness
$\mathbf{H}$	clearance matrix
$\mathbf{I}$	unit matrix
Kn	Knudsen number
L	journal length
M,N	numbers
P	dimensional pressure; $P=p/p_a$
R	journal radius
T_{N-1}	$N-1$-order Chebyshev polynomials
U_0,V_0,W_0	surface velocity components
u,v,w	journal velocity components
x,y,z	reference frame
α	phase angle
λ	gas mean free path
ξ	numerical constant
μ	viscosity
ρ	density
ω	journal angular velocity
ε	eccentricity ratio; $\varepsilon=e/c$
φ,η	circumferential and axial coordinates
ζ	dimensional load carrying capacity
ϕ	attitude angle
ϕ_i	Chebyshev polynomials
χ_i	trigonometric polynomials
Ψ	variable; $\Psi=PH$
$\mathbf{\Psi}$	variable matrix
Λ	bearing number; $\Lambda=(6\mu\omega/p_a)(R/c)^2$

Kn at the minimum film thickness changes between 0.011 and 0.053 [11], which is located in the slip-flow regime. Analytical and numerical investigations of the slip gas flows in microbearings were carried out. Maureau et al. [12] studied the characteristics of eccentric gas-lubricated journal microbearings of infinite length. Pan et al. [13] solved the simplified governing equation and obtained the characteristics of microbearings due to the effects of bearing ends. Ren et al. [14] corrected the mistakes in the equations describing the velocity and moment distributions in [13] and obtained a reasonable understanding of the effects of slip velocity boundary conditions on the characteristics of microbearings. However, the gas-lubricated journal bearings in micro-rotating machinery have a different regime as distinguished from the conventional ones. Moreover, for some special applications such as micro-gas turbine, the gas-lubricated journal bearing should operate at high temperature condition [11]. Lee et al. [11] demonstrated that the slip flow effect becomes significant with temperature increase as well as the lower range of bearing numbers. Li and Shen [16] investigated the effects of gas rarefaction on the dynamic performance of the herringbone groove journal bearings for applications in microsystems. Zhang et al. [17] analyzed the characteristics of gas-lubricated journal microbearings based on the effective viscosity according to the first order slip velocity boundary. Therefore, it is necessary to predict and analyze the performance of gas-lubricated journal microbearings under high-order slip effects for the applications in micro-rotating machinery.

To make a profound understanding of the properties and stability of microbearings in MEMS, this study extends the previous work [18] with the second order slip boundary condition. In this paper, the modified Reynolds equation with the second order slip boundary condition is derived and the mathematic model is presented for the gas-lubricated journal microbearings in Section 2. Section 3 provides numerical analyses and discussion of the properties of the microbearings such as pressure distributions, load carrying capacity and attitude angle, and stability of the bearing-rotor system. Section 4 draws some brief conclusions.

2. Mathematic model

2.1. Modified Reynolds equation

The gas lubrication between two parallel plates can be schematically illustrated in Fig. 1, the upper plate is fixed, and the velocities of the lower plate are U_0, V_0, and W_0 in the x, y, and z directions, respectively. After taking into account the small slope and much smaller spacing in the bearing thickness direction than the length scales in the horizontal directions, one can obtain the following lubrication equations:

$$\begin{cases} \frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \\ \frac{\partial^2 u}{\partial z^2}=\frac{1}{\mu}\frac{\partial p}{\partial x} \\ \frac{\partial^2 v}{\partial z^2}=\frac{1}{\mu}\frac{\partial p}{\partial y} \\ \frac{\partial p}{\partial z}=0 \end{cases} \tag{1}$$

where u, v and w are the gas velocities in the x, y, and z directions, respectively, μ the gas viscosity coefficient, p the gas pressure and ρ the gas density.

According to the prediction provided by Orr [5], the nominal clearance of the gas-lubricated journal bearings is about 2–3 μm and their maximum operated eccentricity ratio is around 0.95 for micro-rotating machinery. Without loss of generality and validity, the second order slip velocity boundary conditions [19] could be selected and given by

$$\begin{cases} u(z=0)=U_0+\frac{2-a}{a}\xi\lambda\frac{\partial u}{\partial z}\Big|_{z=0}-\frac{\xi^2}{2}\lambda^2\frac{\partial^2 u}{\partial z^2}\Big|_{z=0} \\ u(z=h)=-\frac{2-a}{a}\xi\lambda\frac{\partial u}{\partial z}\Big|_{z=h}-\frac{\xi^2}{2}\lambda^2\frac{\partial^2 u}{\partial z^2}\Big|_{z=h} \\ v(z=0)=\frac{2-a}{a}\xi\lambda\frac{\partial v}{\partial z}\Big|_{z=0}-\frac{\xi^2}{2}\lambda^2\frac{\partial^2 v}{\partial z^2}\Big|_{z=0} \\ v(z=h)=-\frac{2-a}{a}\xi\lambda\frac{\partial v}{\partial z}\Big|_{z=h}-\frac{\xi^2}{2}\lambda^2\frac{\partial^2 v}{\partial z^2}\Big|_{z=h} \end{cases} \tag{2}$$

where a is the surface accommodation coefficient, which represents the portion of the total wall-colliding gas molecules that are

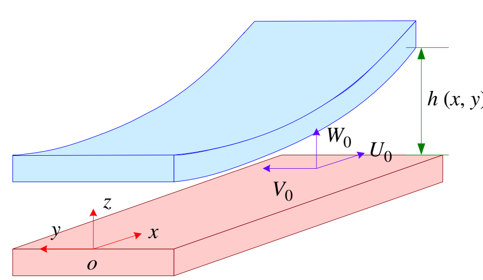

Fig. 1. Illustration of gas lubrication between plates.