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# Effect of air rarefaction on the contact behaviors of air lubricated spiral-groove thrust micro-bearings

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ABSTRACT

The contact behaviors of an air lubricated spiral-groove thrust micro-bearing were investigated. The air bearing force and asperity contact force of the bearing were calculated considering the effect of air rarefaction and surface roughness. The effect of the groove depth and the standard deviation of asperity height was discussed. The results showed that the air bearing force decreases significantly when the air rarefaction is considered. This then leads to an increase in asperity contact force. The depth of spiral grooves and the standard deviation of asperity height also significantly affect the asperity contact force of the bearing.

## 1. Introduction

In air lubricated spiral-groove thrust micro-bearings, rubbing contact is unavoidable during the startup and shutdown operations. Wear and local overheating due to the rubbing contact could result in a failure to generate a hydrodynamic air film. In other words, the bearing would fail to start up [1]. Although the modern surface coating technology has made significant improvements on protecting the air bearing surface, characterizing the contact behaviors of an air lubricated micro-bearing is essential.

Contact behaviors of air lubricated spiral-grooved thrust macro-bearings have been investigated previously. Harp and Salant [2] analyzed the face contact of a spiral-groove macro-bearing with the axial mode of the seal motion. The effects of contact load on the seal dynamics, heat generation, and face deformation were presented. Ruan et al. [3] studied the dynamic contact behaviors of a spiral-groove macro-bearing including the angular motion. The gas film lubrication and face contact were studied considering the gas rarefaction. However, to the authors' knowledge, contact behaviors of spiral-groove thrust micro-bearings have not been reported. For overall understanding of the contact behaviors of the micro-bearing, the effect of air rarefaction and surface roughness should be analyzed in detail, since the micro-bearing have much smaller groove depth and clearance.

In an air lubricated spiral-groove thrust micro-bearing, the groove depth is on the order of a micrometer [4,5]. The Knudsen number Kn of the air flow is larger than 0.001. The classic Reynolds equation with the continuum assumption is no longer valid. The rarefaction effect must be considered for calculating the air bearing pressure [6,7]. The modified Reynolds equation considering the rarefaction effect has been presented in the literature. Burgdorfer [8] modified the Reynolds equation by introducing the first-order slip model. Hsia and Domoto [9] presented the modified Reynolds equation by incorporating the second-order slip model. Mitsuya [10] proposed a 1.5-order modified Reynolds equation. Sun et al. [11] provided a slip model with molecular dynamics. Fukui and Kaneko [12,13] gave the modified model of the Reynolds equation by using the linearized Boltzmann equation with slip boundary conditions. The FK (Fukui-Kaneko) model is suitable for both the low and high Knudsen number regime.

For calculating asperity contact forces, numerous rough contact models have been built by using the finite element method [14–17] and statistical methods [18–21]. The elastic and plastic deformation are considered in the rough contact models [22–24]. Compared to the finite element methods, the statistical methods offer more efficient approach to calculate the contact force of rough surfaces. The asperity contact force of an air lubricated micro-bearing could be calculated by using the statistical GW (Greenwood-Williamson) model. The plastic deformation of the asperities could be assumed to be negligible due to low average contact pressure of the bearing [25].

In this paper, the hydrodynamic air pressure of a spiral-groove thrust micro-bearing is calculated by using a modified Reynolds equation that considers the effects of both the air rarefaction and surface roughness. The asperity contact force is calculated by using the GW contact model. The air film thickness of the bearing is obtained. The effect of angular velocity, the groove depth, as well as the standard deviation of asperity height is discussed.

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**Nomenclature**

| | |
|---|---|
| $A$ | nominal contact area |
| $d$ | standard separation of the two surfaces |
| $D$ | inverse Knudsen number |
| $D_{sum}$ | surface density of the asperity |
| $E^*$ | equivalent elasticity modulus |
| $E_i$ | elasticity modulus of two surfaces, $i$=1, 2 |
| $f$, $g$ | coefficient functions in Eqs. (1c)–(1f). |
| $h$ | film thickness of the air bearing |
| $H$ | normalized film thickness of the air bearing, = $h/h_0$ |
| $h_0$ | average clearance of two surfaces |
| $h_g$ | groove depth |
| Kn | Knudsen number of the air flow |
| $k_i$ | coefficients related to the inverse Knudsen number in Eq. (1b), $i$=1, 2, 3, 4 |
| $K_{ij}$ | components for the element stiffness matrix, $i$, $j$=1, 2, ... 8 |
| $\underset{(n\times n)}{K}$ | stiffness matrix of a global system of equations |
| $n$ | number of nodes |
| $N_j$ | shape function, $j$=1, 2, ... 8 |
| $N_g$ | groove number |
| $P$ | normalized air pressure, = $p/p_a$ |
| $P_0$ | interpolated pressure over the element domain |
| $P_j$ | normalized air pressure at each node, $j$=1, 2, ..., 8 |
| $p_a$ | ambient air pressure |
| $p_o$ | pressure on the outer diameter |
| $p_i$ | pressure on the inner diameter |
| $r_c$ | middle radius of the bearing |
| $r_g$ | spiral radius of the bearing |
| $r_{in}$ | inner radius of the bearing |
| $r_{out}$ | outer radius of the bearing |
| $R_p$ | radius of the asperities |
| $R_i$ | components for the result vector, $i$=1, 2, ... 8 |
| $\underset{(n\times 1)}{R}$ | result vector of a global system of equations |
| $W$ | thrust load of the bearing |
| $W_h$ | hydrodynamic air bearing force |
| $W_a$ | asperity contact force |
| $w_i$ | weighting function, $j$=1, 2, ..., 8 |
| $\delta P$ | unknown quantity of pressure |
| $\delta P_i$ | unknown quantity of pressure at each node, $j$=1, 2, ..., 8 |
| $\underset{(n\times 1)}{\delta P}$ | pressure unknowns of a global system of equations |
| $\theta_r$ | width of ridges |
| $\sigma$ | standard deviation of asperity height distribution, Rq |
| $\sigma_i$ | standard deviation of asperity height distribution of each surface, $i$=1, 2 |
| $\omega$ | angular velocity |
| $\mu$ | viscosity of gas |
| $\gamma$ | Peklenik number |
| $\gamma_i$ | Peklenik number of each surface, $i$=1, 2 |
| $\xi$, $\eta$ | normalized coordinates of the element, $-1\le\xi$, $\eta\le 1$ |
| $\xi_j$, $\eta_j$ | normalized coordinates at node $j$, $\xi_j$ =±1, $\eta_j$ =±1, $j$=1, 2, ... 8 |
| $\nu$ | Poisson's ratio |
| $\theta$, $R$ | axis of the polar coordinate |
| $\alpha$ | spiral angle |
| $\tilde{Q}$ | rarefaction factor |
| $\phi(z)$ | Gaussian distribution of the asperity height |
| $\phi_\theta$, $\phi_R$ | coefficients in Eqs. (1a), (1c) and (1d). |
| $\varepsilon_\theta$,$\varepsilon_R$ | coefficients of the shear flow factor |
| $\phi_s$ | shear flow factor |
| $\Phi_{si}$ | coefficients of the shear flow factor, $i$=1, 2 |
| $\Lambda$ | bearing number |
| $\nabla$ | gradient operator |
| $\Omega$ | domain |
| $\underset{Gauss}{I}$ | Gaussian integration |

## 2. Models

### 2.1. Geometry of an air lubricated spiral-groove thrust micro-bearing

The schematic of the contact behavior of an air lubricated spiral-groove thrust micro-bearing is presented in Fig. 1. The spiral-groove thrust micro-bearing consists of an upper flat surface and an air bearing surface with logarithmic spiral grooves. The spiral equation is $r=r_g\ e^{\theta\ \tan\ \alpha}$. The thrust load of $W$ is assumed to be constant. The pressure on both the outer diameter and inner diameter is set to be 0.1 MPa. Contact behaviors of the micro-bearing refer to the air film lubrication and asperity contacts of the bearing. When the micro-bearing is operating at a low velocity, the hydrodynamic air bearing force is insufficient to sustain the bearing. Asperity contacts occur subsequently. The air bearing force and air film thickness increase with an increase in the velocity. The corresponding asperity contact force decreases. In the model, we assume that the air bearing surface with spiral grooves rotates at the angular velocity of $\omega$. The upper flat surface has an axial motion in the $z$ direction. The effects of the air rarefaction and surface roughness on the contact behaviors of the bearing are considered.

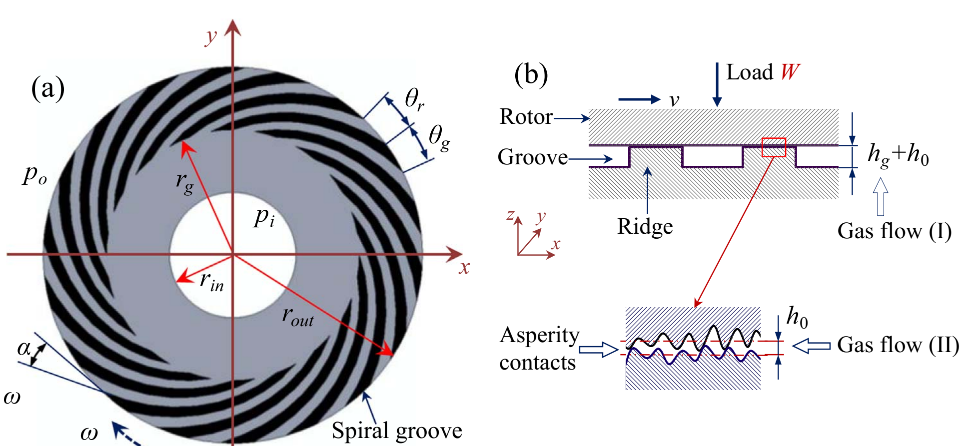


**Fig. 1.** Schematic of the contact behavior of an air lubricated spiral-groove thrust micro-bearing: (a) geometry of the air bearing surface with spiral grooves, (b) hydrodynamic air flow and asperity contact.