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Short Communication

Fluid inertia force effects in hydromagnetic sphere-plate squeeze films

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ABSTRACT

This paper investigates the influences of fluid inertia forces in hydromagnetic sphere-plate squeeze films. Applying the averaged inertia principle, a megnetohydrodynamic pressure gradient equation has been derived. From the results obtained, the combined effects of fluid inertia forces and electrical conducting fluids in the presence of external magnetic fields provide better squeeze film characteristics, and lengthen the operating life of the sphere-plate system as compared to the non-inertia non-conducting-fluid case.

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1. Introduction

Squeezing flow behaviors between spherical bodies play an important role in many applications of engineering science, such as gyroscopes, attitude control apparatuses, ball-bearing damping films, press molding devices and synovial joints. Chan and Horn [1] presents the experimental results providing agreement with the Reynolds lubrication equation for the case of a sphere approaching a flat plate. Matthewson [2] modified the expression of film pressure of Chan and Horn [1] using the boundary conditions for finite wetted regions. Pinkus and Sternlicht [3] obtained the analytical solution for hemispherical squeeze films. Christensen [4] studied the piezo-viscous effects on the normal approaching motion of two spherical bodies. Gould [5] investigated the piezo-viscous effects on the approaching behavior between a spherical body and plate. These contributions [1–5] provide results for squeeze films with a non-conducting viscous fluid.

In order to prevent the variation of viscosity with temperature, the use of electrical conducting liquid metals in fluid film bearings has received great interest. By the application of an external magnetic field, the electrical conducting fluid flow would induce an electrical field resulting in a current density to produce a Lorentz body force acting on the fluid. The increased film pressure is then obtained. Hydromagnetic flows provide many engineering applications, for example, the hydromagnetic braking [6], peristaltic pumping flows of blood [7], microfluidic devices [8], micro-pumps [9], crystal growth control [10] and power generation [11]. Many authors have also investigated the hydromagnetic performances of various squeeze film bearings, such as the noncyclic journal-bearing squeeze film [12], the rotating circular squeeze film [13], the rectangular squeeze film [14], and the sphere-plate squeeze film [15]. Since the influences of fluid inertia forces may become more and more significant as the squeezing velocity increases, a further investigation is motivated. There are many studies to approximate the nonlinear inertia terms, such as the hydromagnetic flows in a slot by Walicka [16], the hydromagnetic performance in slider bearings by Agrawal [17], the end leakage in a squeeze film damper by Tichy [18], the inertial draining in parallel plates by Weinbaum et al. [19], the squeeze film flows of a micropolar fluid by Mahanti and Ramanaiah [20] and a ferrofluid by Lin [21]. In this study, the effects of fluid inertia forces in the sphere-plate squeeze film with an electrical conducting fluid in the presence of an external magnetic field is investigated. The pressure gradient equation will be derived following the means of Mahanti and Ramanaiah [20] and Lin [21]. Compared to the non-inertia non-conducting-fluid case by Matthewson [2] and the non-inertia electrical-conducting-fluid case by Chou et al. [15], the performance characteristics of the sphere-plate squeeze film are obtained and discussed in terms of the variation of inertia parameter and the magnetic parameter.

2. Analysis

Fig. 1 describes the physical geometry for a sphere-plate squeeze film with an electrical conducting fluid in the presence of an external magnetic field. The upper sphere of radius R is approaching the lower plate with a squeezing velocity $V_{sq} = -\partial h/\partial t$. A uniform external magnetic field B_0 is applied perpendicular to the

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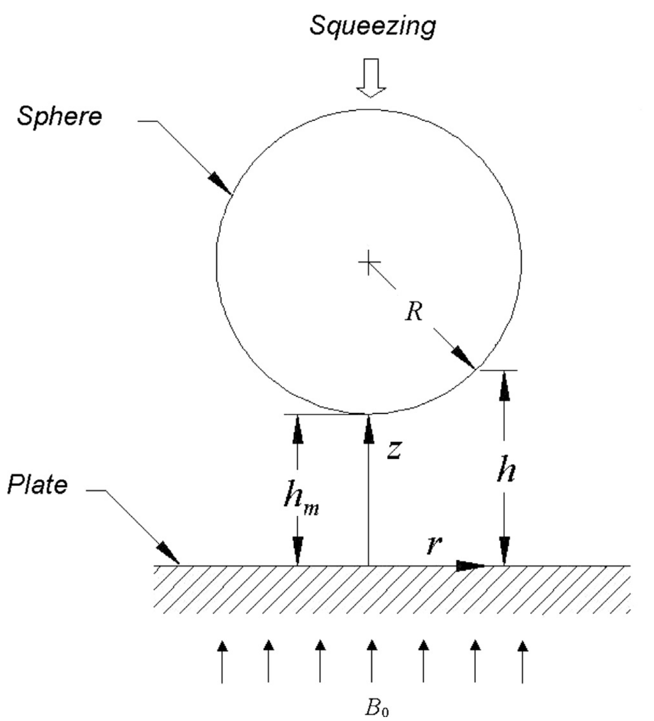

Fig. 1. Physical geometry for a sphere-plate squeeze film with an electrical conducting fluid in the presence of an external magnetic field.

plate along the vertical direction, z. Provided $r \ll R$, the local film thickness h depending on the radial coordinate r is expressed as Matthewson [2],

$$h = h_m + \frac{r^2}{2R} \tag{1}$$

where h_m denotes the minimum film thickness. Assume that the thin-film lubrication theory of Pinkus and Sternlicht [3] is applicable, the body force is negligible except for the Lorentz force, and the induced magnetic field is small as compared to the external applied field. According to the hydromagnetic flow model [22], the magnetohydrodynamic momentum equation including the convective inertia terms and the incompressible continuity equation can be expressed in polar coordinates as:

$$\rho\left(v_r\frac{\partial v_r}{\partial r} + v_z\frac{\partial v_r}{\partial z}\right) = -\frac{\partial p}{\partial r} + \mu\frac{\partial^2 v_r}{\partial z^2} - \sigma B_0^2 v_r \tag{2}$$

$$\frac{\partial p}{\partial z} = 0 \tag{3}$$

$$\frac{1}{r}\frac{\partial(r v_r)}{\partial r} + \frac{\partial v_z}{\partial z} = 0 \tag{4}$$

The symbols v_r and v_z are the velocity components in the the r and z directions, respectively, ρ is the mass density, p is the pressure, μ is the dynamic viscosity,σ is the electrical conductivity of the fluid. The non-slip boundary conditions for velocity components are

$$v_r|_{z=0} = 0, \qquad v_z|_{z=0} = 0 \tag{5}$$

$$v_r|_{z=h} = 0, \qquad v_z|_{z=h} = -V_{sq} = \frac{\partial h}{\partial t} \tag{6}$$

Since the local film thickness is assumed to be small as compared to the radius of the sphere, the convective fluid inertia forces can be regarded as constant over the film thickness. Therefore, the inertia terms in the momentum equation are treated by the mean value across the film thickness.

$$\frac{\rho}{h}\int_{z=0}^{z=h}\left(v_r\frac{\partial v_r}{\partial r} + v_z\frac{\partial v_r}{\partial z}\right)dz = -\frac{\partial p}{\partial r} + \mu\frac{\partial^2 v_r}{\partial z^2} - \sigma B_0^2 v_r \tag{7}$$

Performing the integration by applying the continuity equation and the velocity boundary conditions, the above equation can be expressed as the following second order equation.

$$\mu\frac{\partial^2 v_r}{\partial z^2} - \sigma B_0^2 v_r = \frac{\partial p}{\partial r} + \frac{\rho}{h}\left(\frac{\partial}{\partial r}\int_{z=0}^{z=h} v_r^2 dz + \frac{1}{r}\int_{z=0}^{z=h} v_r^2 dz\right) \tag{8}$$

Introduce a modified pressure gradient function containing the pressure gradient, $\partial p/\partial r$.

$$g_p = \frac{\partial p}{\partial r} + \frac{\rho}{h}\left(\frac{\partial}{\partial r}\int_{z=0}^{z=h} v_r^2 dz + \frac{1}{r}\int_{z=0}^{z=h} v_r^2 dz\right) \tag{9}$$

As a consequence, the above second order equation can be rewritten as

$$\frac{\partial^2 v_r}{\partial z^2} - \frac{\sigma}{\mu}B_0^2 v_r = \frac{1}{\mu}g_p \tag{10}$$

Solving the equation subject to the velocity boundary conditions, one can obtain

$$v_r = \frac{h_{m0}^2}{\mu} \times \frac{\cosh(Mz/h_{m0}) - 1 - \tanh(0.5Mh/h_{m0})\sinh(Mz/h_{m0})}{M^2} \times g_p \tag{11}$$

where h_{m0} denotes the initial minimum film thickness, and M represents the magnetic Hartmann number defined by

$$M = h_{m0}B_0\sqrt{\frac{\sigma}{\mu}} \tag{12}$$

The equation for the squeeze motion is

$$\int_{z=0}^{z=h} v_r dz = \frac{1}{2}rV_{sq} \tag{13}$$

By the substitution of v_r and V_{sq}, one can derive the expression of the modified pressure gradient function after performing the integration.

$$g_p = -6\mu \times \frac{r}{f_A(h, M)}V_{sq} \tag{14}$$

where

$$f_A(h, M) = \frac{12Mh/h_{m0} - 24\tanh(0.5Mh/h_{m0})}{M^3} \times h_{m0}^3 \tag{15}$$

Combining Eqs. (9) and (15), one can obtain the pressure gradient, $\partial p/\partial r$, expressed as

$$\frac{\partial p}{\partial r} = -\frac{6\mu r}{f_A(h, M)} \times V_{sq} - \frac{\rho}{h}\left(\frac{\partial}{\partial r}\int_{z=0}^{z=h} v_r^2 dz + \frac{1}{r}\int_{z=0}^{z=h} v_r^2 dz\right) \tag{16}$$

Substituting the expressions of v_r and g_p and performing the integration, one can derive the pressure gradient equation for hydromagnetic sphere-plate squeeze films including the effects of fluid inertia forces.

$$\frac{\partial p}{\partial r} = -\frac{6\mu r}{f_A} \times V_{sq} - \frac{9\rho[3Rf_Af_B - r^2(2f_Bf_C - f_Af_D)]r}{Rhf_A^3} \times V_{sq}^2 \tag{17}$$

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