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Coriolis effects on torque transmission of hydro-viscous film in parallel disks with imposed throughflow

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ABSTRACT

The imposed throughflow into rotating parallel disk system is to decrease temperature rise of hydro-viscous film flow, but the induced Coriolis effects are usually underestimated on torque transmission. The analytical expressions of thin-film parameters are obtained based on Navier-Stokes equations with the method of approximate analytical iteration. The Coriolis force and the corresponding influence on torque transmission are analyzed by analytical calculation and experimental verification. The results show that the tangential Coriolis force serves as resistance to the viscous torque transmission and the Coriolis torque loss can lead to primary reduction of efficiency among all motion effects. Therefore, the Coriolis effects should be paid more attention for the practical designs and applications of rotating hydro-viscous parallel-disk systems with imposed throughflow.

1. Introduction

The thin shear flows between rotating parallel disks are typical problems which have been investigated by many researchers through various theoretical and experimental methods, because the parallel-disk flows have a large number of engineering applications such as torque transmission [1–3] and lubrication cooling [4–6]. In the field of torque transmission, like hydro-viscous clutch [2], the torque is able to be transferred by shear stress of viscous thin film between friction disks.

Besides serving as the working medium [7], the cooled oil must be supplied all the time into the hydro-viscous driving devices so as to bring out lots of heat coming from viscous dissipation and keep film temperature at a low level, during which the larger the throughflow rate is, the less the film temperature rise will be. As a result, the less the viscosity reduction will be. Thus the efficiency of power transmission will be kept high. However, although larger imposed throughflow can ensure steady and efficient torque transmission, the enhanced radial velocity component will result in increasing tangential Coriolis force based on the equation of Coriolis force $F_{Cor\_\theta} = 2\rho\omega v$ (ρ is density, ω is relative rotary speed of two disks and v is radial velocity component). Therefore, the resulting influence of tangential Coriolis force on torque transmission must be paid more attention so that the balance between throughflow rate and Coriolis effects can be controllable.

In the past decades, a great number of literatures about rotating flows in parallel disk have been reported. The torque transmission of rotating enclosed-parallel disks has earlier got much attention, and a series of empirical formulas about torque coefficient were summarized [8–11] but basically only suitable for the cases of high Reynolds number. However, from the equation of F_{Cor_θ} we can know that F_{Cor_θ} may become significant for the case of high rotating speed, so it may be more reasonable for these researches to take the Coriolis terms into account. Besides, for the rotating flows between parallel disks with imposed throughflow, Conover [12] and Poncet et al. [13] have ever measured and analyzed the velocity profiles under different throughflow rate, and their results indicated that the throughflow rate could significantly influence the flow velocity components. Especially, in their literatures we find that different throughflow rate could lead to different distributions of tangential velocity component, which was not further investigated unfortunately. According to our inference, it may be the tangential Coriolis force that functions to affect the tangential velocity profiles.

In addition, there were also many published literatures about the Coriolis effects of rotating thin film flow. For film flows on single rotating disk, Leshev and Peev [14] derived the analytical expressions with Coriolis effects from simplified dimensional NS equations and it was experimentally confirmed that the expressions were more accurate than those without Coriolis effects. Myers and Lombe [15] as well as Momoniat and Mason [16] improved the classical analytical relation between height and flow rate of rotating film by selecting proper dimensionless scales to highlight the Coriolis effects. For rotating film flows in parallel disks but without imposed throughflow, Waters and

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Cummings [17] investigated the Coriolis effects in the rotating Hele-Shaw cell, and after comparison they pointed that the models neglecting Coriolis forces has more appreciable errors in prediction performance. Mehdizadeh and Oberlack [18] also emphasized that the Coriolis forces could highly effected the structures of film flow in rotating disks and they also retained the Coriolis terms in governing equations.

To the author's knowledge, few literatures were reported about the Coriolis effects on viscous torque transmission of rotating thin-film with imposed throughflow. Therefore, in the present paper, our objective focuses on how the Coriolis forces affect the hydro-viscous transmission characteristics of parallel disks. In the second section, the physical model of thin film is presented and the analytical expressions of thin film are derived. The test rig is introduced in the third section. The fourth section is to discuss the effects of Coriolis forces on torque transmission and the results are validated in experiment. The last section draws some conclusions.

2. Models

2.1. Physical model

The physical configuration of axisymmetric thin film with imposed throughflow is displayed in Fig. 1. It is located in rotating cylindrical polar coordinate (r, θ, z) and the r-axis is on the driven disk surface. The annular film flow is considered as incompressible and Newtonian fluid. The viscous fluid with throughflow rate Q is imposed into the disk clearance from the inner side and comes out from the outer side (the ambient pressure $p_a = 0$), during which the thin film forms with thickness h_0, inner radius R_1, and outer radius R_2. The driving disk rotates about z-axis with rotary speed ω_1 and driving torque M_{in} while the rotary speed of driven disk is ω_2 with driven torque M_{out}. The radial pressure gradient will play a leading role in radial direction due to the effect of imposed throughflow so that the radial velocity component can't be ignored at all. The tangential Coriolis force F_{Cor_θ} on fluid particle is also shown in Fig. 1. What's more, the thermal effect of film flow is negligible in this research because the imposed flow can bring most heat out.

2.2. Analytical solution

The hydro-viscous film in parallel disks is usually treated as laminar flow because of its high flow viscosity and small film thickness. The axial velocity component is negligible as its order of magnitude is lower than the other two components. It is also confirmed that some usual assumptions in thin-film lubricant theory are applicable. Nevertheless only the inertial forces are neglected in present research, while the Coriolis and centrifugal forces are the leading factors and are retained. The final momenta equations can be written as

$$-\frac{u^2}{r} - 2A\omega u - \omega^2 r = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \nu\frac{\partial^2 v}{\partial z^2} \tag{1.1}$$

$$\frac{vu}{r} + 2A\omega v = \nu\frac{\partial^2 u}{\partial z^2} \tag{1.2}$$

$$\frac{\partial p}{\partial z} = 0 \tag{1.3}$$

where (u,v) the velocity components in tangential and radial direction respectively, $\omega = \omega_1 - \omega_2$ is the relative rotary speed of two disks, p the film pressure, $\nu = \mu/\rho$ is the kinematic viscosity, μ is the dynamic viscosity, $A = 0$ and $A = 1$ mean the Coriolis effects are ignored and considered respectively. The no-slip boundary conditions are used on two disk surfaces, namely

$$z = 0 : u = r\omega_2, v = 0; z = h_0 : u = r\omega_1, v = 0 \tag{2}$$

What's more, integrating the radial velocity component across the film thickness yields the continuity equation:

$$Q = 2\pi r \int_0^{h_0} v dz \tag{3}$$

By integrating Eqs. (1.1) and (1.2) with respect to z twice from 0 to z and taking boundary conditions (2), the velocity components can be expressed as:

$$v = \frac{1}{2\mu}\frac{\partial p}{\partial r}z(z-h_0) + \frac{1}{\nu}X(r,z) - \frac{1}{\nu}\left(1-\frac{z}{h_0}\right)X(r,0) - \frac{1}{\nu}\frac{z}{h_0}X(r,h_0) \tag{4}$$

$$u = r\left(\frac{z}{h_0}\omega + \omega_2\right) + \frac{1}{\nu}Y(r,z) - \frac{1}{\nu}\left(1-\frac{z}{h_0}\right)Y(r,0) - \frac{1}{\nu}\frac{z}{h_0}Y(r,h_0) \tag{5}$$

where

$$X(r,z) = \int_0^z\int_0^z\left(-\frac{u^2}{r} - 2A\omega u - r\omega^2\right)dzdz \tag{6}$$

$$Y(r,z) = \int_0^z\int_0^z\left(\frac{vu}{r} + 2A\omega v\right)dzdz \tag{7}$$

Substituting Eq. (4) into Eq. (3) and then considering the pressure-outlet boundary condition at the outer side of thin film ($p = p_a = 0$ at

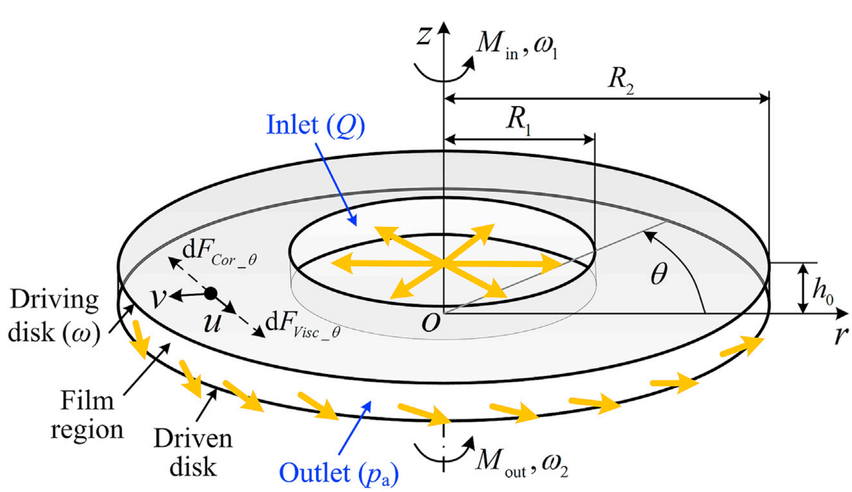

Fig. 1. Geometry and notations of thin-film flow.