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Wall slip and hydrodynamics of two-dimensional journal bearing

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Abstract

In the present paper, based on the limiting shear stress model, a multi-linearity finite element algorithm and quadratic programming technique are used to study the influence of wall slip on the hydrodynamic lubrication performance of a two-dimensional journal bearing (finite length journal bearing). It is found that if the lubricated surfaces are designed as homogeneous slip surfaces, the hydrodynamic force will be decreased. If the shaft surface (rotation) is a slippery surface with very low limiting shear stress, almost no fluid load support can be generated. If the sleeve surface is designed as the homogeneous slip surface, a low fluid load support together with a small friction drag can be obtained. However, if the sleeve surface is designed as an optimized slip surface with a slip zone in the inlet region, a high load support and low friction coefficient can be obtained. Optimization of the shape and the size of the slip zone can give the journal bearing many advanced properties.

Keywords: Wall slip; Journal bearing; Lubrication

1. Introduction

It is well known that there is a core concept in classical fluid mechanics—'no slip' at the liquid-solid interface, i.e., no relative motion occurs at the wall [1,2]. For centuries, although the no-slip boundary condition (BC) has been successfully applied to explain many macroscopic experiments, the no-slip BC has been doubted by scientists. For instance, more than a century ago, Helmholtz and Piotrowski [3] reported some evidences of slip on the interface of a solid and a liquid. But, their experiment was criticized and doubted by Wetham [4], Ladenburg [5], and some others, and was considered due to a lack of experimental precision. However, Schnell [6] in 1956 and Churaev et al. [7] in 1984 gave again some evidences that slip took place on hydrophobic solid surface of a capillary although their experimental precision might not be high enough. During the last decades, with the advancement of the experimental techniques, such as nano-particle image velocimetry (NPIV) [8], atomic force microscope (AFM) [9–11], surface force apparatus (AFM) [12], etc, a number of researchers have found evidences that wall slip occurs not only on hydrophobic surfaces [8,9,12], but also on hydrophilic surfaces [10,11,13]. The NPIV technique is a direct observation method with a measurement precision depending on the size of the nano-particles. The AFM and SFA are indirect observation techniques based on the assumption that the slip occurs exactly on the interface of solid and liquid. In addition, molecular dynamics simulation for a Couette flow also indicates that slip occurs on the solid wall [14]. Although whether the wall slip occurs exactly at the interface between fluid and solid, and how to decouple the effects of the factors, such as the surface wettability, surface roughness, fluid viscosity, nanobubbles and so on, are still questionable [15], the slip evidence has been generally accepted.

The so-called slip length model [16–19] and the limiting shear stress model [20–24] are usually used to describe a wall slip. The slip length model, proposed first by Navier [16], states that the slip velocity is proportional to the liquid shear rate evaluated at the interface, and the 'slip length', the fictive distance below the solid surface where the

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Nomenclature

Symbols

A	area of fluid film domain
c	radial clearance
D	diameter of bearing shaft, $= 2R \approx 2R'$
e	eccentricity
f	slip control function
f^*	friction force
h	fluid film thickness
$J(p)$	functional symbol
k	proportionality coefficient
L	length of journal bearing (in y direction)
L_{s1}, L_{s2}	size parameters of the slip zone on the sleeve surface
N	number of polygon sides
p	film pressure
p_s	film pressure corresponding to q_s
q_s	known normal volume flow at boundary
R	radius of shaft
R'	radius of sleeve $R' \approx R$
S_q	the boundary of the fluid domain
t	time
u	fluid velocity
$\bar{u}_a, \bar{u}_b$	fluid velocities at surfaces a and b
$u^s_a, u^s_b,$	fluid slip velocities at surfaces a and b
U	sliding velocity of journal bearing $= R\omega$
w	fluid film load support
x,y	coordinates in Reynolds equation
β_i	the angle corresponding to the ith slip control equation
ε	eccentricity ratio $= e/c$
ϕ	fluid film load support angle
γ	Lagrangian multiplier
η	fluid viscosity
θ	angular coordinate
θ_s	the angle corresponding to the slip zone
θ_{out}	the termination angle of Reynolds boundary conditions
τ	shear stress
τ_α	surface shear stress ($\alpha = a, b$)
$\tau_{x\alpha}, \tau_{y\alpha}$	surface shear stress in x and y direction ($\alpha = a, b$)
$\tau_{\mathrm{L}\alpha}$	surface limiting shear stress ($\alpha = a, b$)
$\tau^*_{\mathrm{L}\alpha}$	approximation of the surface limiting shear stress($\alpha = a, b$)
τ_0	initial limiting shear strength
ω	angular velocity of journal
ξ, ζ	coordinates for the journal bearing load support
$\lambda^{(i)}_\alpha$	control variable or absolute value of slip velocity
$v^{(i)}_\alpha$	slack variable

Dimensionless parameters

$F = f^* c/(\eta\omega R^2 L)$
$K_\alpha = k_\alpha R/c$
$P = pc^2/(\eta\omega R^2)$
$T_{0\alpha} = \tau_{0\alpha} c/(\eta\omega R)$
$T_{\mathrm{L}\alpha} = \tau_{\mathrm{L}\alpha} c/(\eta\omega R)$
$W = wc^2/(\eta\omega R^3 L)$
$\bar{y} = y/(L/2)$
$\mu = F/W$

Sub- and Superscripts

i	the ith control equation
0	initial
s	boundary (subscript) or slip (superscript)
slip	the journal bearing with a slip zone on the sleeve or the shaft surface
no-slip	the traditional journal bearing
α	*a, b* indicating upper surface *a* and down surface *b*

velocity extrapolates linearly to zero, is the proportional constant. When the shear rate is low, the slip length model can describe the slip behavior. However, experiments [12,25,26] and molecular dynamic (MD) simulation [14] show that the slip length is not a constant while the shear rate is very high. The limiting shear stress model assumed that there is a limiting shear stress at the solid–liquid interface. It was first proposed for describing the lubricant rheology at high pressure [20,21] and later was investigated by some other researchers [22–24,27,28]. The limiting shear stress, τ_{L}, is usually given by

$$\tau_{\mathrm{L}} = \tau_0 + kp, \tag{1}$$

where τ_0 is the initial limiting shear stress, k is a proportional constant, and p is the fluid pressure. In a wetting interface of oil and steel, the reported initial shear strength usually is very large, varying from 0.16 to 8 MPa [21,27,29], but the results should be treated with care because it is difficult to measure the parameter. The proportionality coefficient, k, has been examined in several ways and by a few research groups [23,24,27,29] with the results that range from about 0.007 to 0.15 and the variation is found to be temperature-dependent. Recently, it was reported that the slip plane might occur within the solid-like liquid film if the pressure of the film confined between two highly wetting surface is very high [30], where the temperature and shear rate were localized, but not at the wall. At such a high pressure the viscosity–pressure relation has to be considered and thus the lubricant viscosity may be so high that it looks like a solid behavior (near the glass transition of the lubricant). However, for a nonwetting or partially wetting surface, the limiting shear