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A velocity-slip model for analysis of the fluid film in the cavitation region of a journal bearing

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ABSTRACT

The Reynolds equation is derived by using the continuity equation, Navier–Stokes equation and slip length equation within cavitation region. A finite difference method are used to obtain the static and dynamic parameters of journal bearing. A comparison with the available experimental results reveals that the load capacity is well predicted by the present model. The results also show that slip effects in the cavitation region have an influence on the oil film pressure, the load capacity, the dynamic characteristics coefficients and the stability of journal bearing. The good behavior of the proposed algorithm is further illustrated in one example of a dynamically loaded journal bearing, and evolution with time of the journal center is well obtained.

1. Introduction

Cavitation phenomenon occurs currently in oil lubricated journal bearing for diesel engines of marine or power station applications and automotive engines. Because of fluctuation of radial force from crankshaft, instability of lubricant flow, variation of oil pressure can be sufficient to produce bubble inception and collapse within the oil film of journal bearing.

The treatment of cavitation phenomena is a key concern in the modeling of lubrication problems. Several numerical methods have been developed to deal with this problem. Reynolds condition [1] are the most widely used at present, whereas, oil flow cannot be determined because mass is not conserved within the cavitation region. To account for the film reformation and ensure mass continuity, Jakobsson, Floberg [2] and Olsson [3] proposed a JFO cavitation model, which are realistic but not easily implemented since the cavitation boundaries are not a priori known. The mass conserving Elrod–Adams model [4–6] is now commonly accepted as a universal cavitation algorithm for simulation in hydrodynamic lubrication involving cavitation. This model contains two unknown fields, the pressure p and the fluid fraction α, so that the equations describing the full film area and cavitated area could be combined into a unified general equation.

Among the above models, zero flow velocity is assumed at a wall of journal bearing, and a "no-slip" boundary condition is used to analyze continuum fluid flow within the whole oil film. However, molecular dynamics simulations have shown that the slippage can be conditioned through changes in fluid-surface interactions [7,8]. Several reasons have been proposed for the slip at the solid-liquid interface: molecular slip [9], a decrease in the viscosity of a boundary layer [10], and the air trapped between the surface structures [11,12]. Ruckenstein and Rajora [11] suggested that there may be a gas “gap” at the interface between the solid and the liquid caused by the different nature of the two materials. Depending on the characteristics of the liquid-solid interface, two different classes of superhydrophobic states are exhibited, namely the so-called Wenzel and Cassie states [13,14]. In particular, gas gaps or nanobubbles at the interface between lubricant and bearing was addressed in the cavitation zone of journal bearing by Groper et al. [15] and Sun et al. [16].

Recently, some studies by Zhang et al. [17] and Rao et al. [18] have reported that, the boundary slippage occurs on the texturing surface of journal bearing or in a high speed condition. However, there are no reports available in the literature with regard to a slip effect in the cavitation zone of a journal bearing. The slip effect in the cavitation zone can change the cavitation boundary conditions of fluid lubrication, and influence the static and dynamic characteristics of the journal bearing as well as the stability of the rotor-bearing system. In the study, a new theoretical model is proposed to solve the velocity-slip problem in the cavitation zone of the journal bearing. The present work aims at evaluating static,

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Nomenclature

C_{XX}, C_{YY}	direct damping coefficient (Ns/m)
C_{XY}, C_{YX}	cross-coupled damping coefficients (Ns/m)
h	local bearing clearance (m)
h_0	radical clearance (m)
j, k	node along φ and z directions
K_s	slip coefficient at gas-liquid interface
K_{st}	the effective bearing stiffness (N/m)
K_{XX}, K_{YY}	direct stiffness coefficient (N/m)
K_{XY}, K_{YX}	cross-coupled stiffness coefficients (N/m)
L	axial length of journal bearing (m)
L_s	slip length (m)
M	mass of the shaft or the mass of system (Kg)
M_{cr}	the critical mass (Kg)
M_x, M_y, M_z	volume flows in x, y, *and* z (m^3/s)
n	the number of time step
n_1,n_2	fluid film pressure (Pa)
p	fluid film pressure (Pa)
R	journal radius (m)
t	time (s)
Δt	time step (s)
T_0	working temperature (°C)
U	journal surface circumferential velocity component (m/s)
v_x, v_y, v_z	x, y, z component of fluid velocity (m/s)
w	applied load (N)
w_X, w_Y	X, Y component of the applied load (N)
W	load carrying capacity (N)
W_X, W_Y	X, Y component of the load carrying capacity (N)
x	circumferential coordinate (m)
y	radial coordinate (m)
z	axial coordinate (m)
$\Delta\varphi$, Δz	grid spacing along φ and z directions (rad, m)
X, Y	X, Y coordinates of journal center (m)
$\dot{X}$,$\dot{X}$	X, Y component of velocity perturbation of journal center (m/s)
α	local fluid volume fraction
β	local gas volume fraction
μ_l	viscosity of liquid (Ns/m^2)
μ_a	viscosity of air (Ns/m^2)
δ	pure air layer of thickness (m)
θ	attitude angle (°)
ξ	convergence tolerance
ε	the eccentricity
Ω	rotating speed (rpm)
g	gravitational acceleration (m/s^2)
γ_{st}	the instability whirl frequency (1/s)
φ	the dimensionless variables ($\varphi = x/R$)
$\bar{y}$	the dimensionless variables ($\bar{y} = y/h$)
$\bar{z}$	the dimensionless variables ($\bar{z} = 2z/L$)
$\bar{h}$	the dimensionless variables ($\bar{h} = h/h_0$)
$\bar{p}$	the dimensionless variables ($\bar{p} = h_0^2 p/\left(6\Omega\mu R^2\right)$)
T	the dimensionless variables ($T = Ut/(2\pi R)$)

dynamic characteristics and stability of the journal bearing when considering the slip flow over the cavitation zone. The study lets us to better understand the influence of a slip effect on the journal bearing, which in turn casts light on their potential engineering applications.

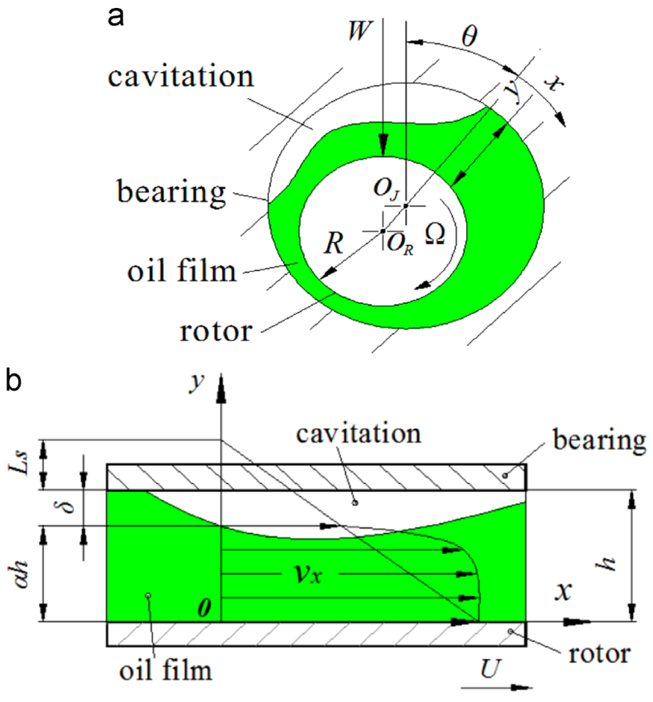

Fig. 1. Schematic of (a) a journal bearing and (b) a slip velocity.

2. Theoretical models

2.1. Slip length in the cavitation region

Fig. 1(a) shows a typical cylindrical journal bearing. The inner part is a rotor with a radius R and a rotational speed Ω (surface velocity $U = R\Omega$), and the outer part is a bearing with inner radius $R + h_0$. Within the converging film region, the hydrodynamic pressure rises to a peak, decreasing to ambient pressure at the end sides. In zones where the film thickness locally increases, the fluid pressure may drop to ambient, or below ambient to its vapor pressure causing lubricant cavitation.

The problem to be considered is that of a laminar flow slip effect in the cavitation zone of a journal bearing, as shown in Fig. 1 (b). A cavity layer separates oil lubricant from a jounal bearing wall in the cavitation zone by Mistry et al. [19] and Groper et al. [15]. Under this condition, the large cavity adheres to the bearing wall in a state of laminar flow, leading to a smooth interface between gas and liquid phase. As an ideal case, a slip length L_s due to the pure air layer of thickness δ can be represented by Choi et al. [20]

$$\begin{cases} L_s = \delta\left(\frac{\mu_l}{\mu_a} - 1\right) \\ \delta = (1-\alpha)h \end{cases} \tag{1}$$

where μ_l and μ_a are the viscosity of liquid and air, respectively, α is local air volume fraction ($\alpha = 1$ in oil film zone, and $0 < \alpha < 1$ in the cavitation zone), h is local bearing clearance. A effective slippage is expected due to the sizable viscosity difference between liquid and air, larger with a thicker air layer. Thus, the cavitation boundaries should be modified to make it suitable for the slip flow in the journal bearing.

2.2. Derivation of Reynold equation

The methodology used in deriving the Reynolds equation is quite similar to that employed to obtain the conventional Reynolds