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Performance behaviour of elliptical-bore journal bearings lubricated with solid granular particulates

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ABSTRACT

Journal bearings operating in hot environments and at high temperatures experience accelerated degradation of lubricating oils. In such situations, dry granular particulates have emerged as potential media for providing lubrication in journal bearings in place of lubricating oils. Granular particulates do not degrade thermally, even at considerably high temperatures. This work explores the static and dynamic performance characteristics of elliptical-bore journal bearings lubricated with granular particulates. It is found that a bearing lubricated with a larger size (2 μm) particles offers better performance compared with that using smaller size (1 μm) particles. Bore ellipticity reduces the load-carrying capacity and increases side leakage and the coefficient of friction; however, rotor stability is marginally improved at low eccentricity ratios (<0.6), followed by significant improvement at high eccentricity ratios (>0.6).

Introduction

Conventional lubricating oil employed in journal bearings operating in hot environments at high temperatures deteriorates due to its thermal instability, causing rapid degradation of the oil (Stachowiak & Batchelor, 2013). For effective lubrication of bearings, an excessive rise in the temperature of the lubricant should be avoided. The Arrhenius rate law states that for every 10 °C rise in temperature, the rate of the chemical reaction doubles; in lubricating oil, this causes chain breakage of the molecules. Moreover, broken molecules interact differently from normal lubricant molecules. This causes polymerization, which leads to sludge formation and prevents the lubricating behaviour of oil, i.e., its ability to participate effectively in mixed and hydrodynamic lubrication. This results in the loss of load-sustaining capability of the bearing. Dry granular particulates have the potential to act as lubricants in bearings working in hot environments and under extreme operating conditions (Iordanoff, Berthier, Descartes, & Heshmat, 2002; Khonsari, 1997; Wornyoh, Jasti, & Higgs, 2007).

Dry granular powders have been widely employed as lubricants in mechanical devices. Heshmat and co-researchers have extensively studied the behaviour of powder lubrication in machine elements, such as dampers (Heshmat & Walton, 1992, 1993), slider/pad bearings (Heshmat, 1992, 2000; Heshmat & Heshmat, 1999), and journal bearings (Heshmat & Brewe, 1995, 1996; Higgs, Heshmat, & Heshmat, 1999; Kaur & Heshmat, 2002). Based on these studies, the researchers have reported that the pressure developed at the interface by powder lubricants is remarkably similar to that of liquid lubricants. Experiments on a three-pad journal bearing have been conducted using MoS_2 (Heshmat & Brewe, 1995) and WS_2 (Heshmat & Brewe, 1996) powders to explore the performance of a bearing operating at 53.3 m/s (30,000 rpm) speed under lightly loaded conditions (unit load 0.35 MPa) and subjected to temperatures as high as 400 and 600 °C, respectively. Higgs et al. (1999) found that, at high speed and in extremely hot environments, MoS_2 is more acceptable as a lubricant than WS_2. Similarly, based on an experimental study of a journal bearing (operating parameters: unit load 0.65 MPa; speed 53.3 m/s, i.e., 30,000 rpm), Kaur and Heshmat (2002) concluded that powders have great potential as lubricating materials for application in hot environments.

To numerically understand the performance of powder-lubricated bearings for a wide range of operating parameters, Dai, Khonsari, and Lu (1994) and McKeague and Khonsari (1996a, 1996b) used grain theory (proposed by Haff (1983)) to develop mathematical models applicable to lubrication. In the proposed models, the powder particles were assumed to behave as molecules of granular fluid. Dai et al. (1994) reported an analytical model for a slider bearing that considers energy fluctuations due to inter-grain collisions and particle slippage at boundaries. McKeague and Khonsari (1996b) studied Couette flow in powder lubrication by

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Nomenclature

B	mean fluctuation velocity, m/s
c_{ij}	damping coefficient, Ns/m
C_r	radial clearance, mm
C_{ij}	dimensionless damping coefficient ($c_{ij}C_r/W$)
d	particle diameter, μm
D	diameter of bearing, mm
F_X	bearing force in X-direction, N
F_Y	bearing force in Y-direction, N
F_s	total shear force on the journal, N
e	eccentricity, mm
f	coefficient of friction for elliptical bore
f_0	coefficient of friction for circular bore
$\mathbf{f}$	body force per unit mass, N/Kg
f_x, f_y, f_z	components of body force per unit mass $\mathbf{f}$, N/Kg
$\bar{F}_s$	dimensionless friction force, $\bar{F}_s = (F_s/\eta_0 UL)(C_r/R)^2$
G	non-circularity parameter, $(R_{max} - R_{min})/C_r$
h	film thickness, mm
$\bar{h}$	dimensionless film thickness, h/C_r
h_{min}	minimum film thickness, μm
I	energy dissipation
K	thermal diffusivity
k_{ij}	stiffness coefficient, N/mm
K_{ij}	dimensionless stiffness coefficient, $k_{ij}C_r/W$
L	bearing width, mm
m	rotor mass, kg
M_{cr}	stability parameter for elliptical bore
M_{cr0}	stability parameter for circular bore
N	speed, rpm
p	hydrodynamic pressure, Pa
Q_x	volumetric flow rate per unit width in x-direction, m^2/s
Q_z	volumetric flow rate per unit width in z-direction, m^2/s
Q_l	side leakage, m^3/s
$\bar{Q}_l$	dimensionless side leakage, $\bar{Q}_l = Q_l/(UC_r)$
R	radius of journal, mm
R_b	radius of elliptical bore, mm
R_{max}	major radius of elliptical bearing, mm
R_{min}	minor radius of elliptical bearing, mm
s	average surface separation between two neighbouring particles
t	time, s
u_x, u_y, u_z	particle flow velocity in x, y, and z directions
U	surface velocity, m/s
$\bar{v}$	average particle fluctuation velocity, m/s
V	particle flow speed, $\sqrt{u_x^2 + u_y^2 + u_z^2}$
W	load on the bearing, N
$\bar{W}$	dimensionless load-carrying capacity, $\bar{W} = (W/\eta_0 UL)(C_r/R)^2$
x, y, z	coordinates for Reynolds equation
X, Y, Z	coordinates for film forces, stiffness and damping coefficients
$\Delta X, \Delta Y$	displacement perturbation in X and Y directions, respectively, m
$\Delta\dot{X}, \Delta\dot{Y}$	velocity perturbation in X and Y directions, respectively, m/s
δ	orientation of the major axis of elliptical bearing from load line, rad
ε	eccentricity ratio, e/C_r
η	viscosity, Pa s
η'	average flow viscosity across the film, Pa s
η_0	reference viscosity, Pa s
Λ	$h_{min}/(\sigma_1 + \sigma_2)^{0.5}$
ρ	density, kg/m^3
σ_1, σ_2	roughness on journal and bearing surfaces, respectively, μm
θ	angular coordinate, rad
ϕ	attitude angle, rad
ω	journal angular velocity, rad/s

developing an appropriate theory. Tsai and Jeng (2002, 2006) investigated the effects of grain characteristics on the performance of journal bearings.

Since the last decade, attempts have been made by various researchers (Jang & Khonsari, 2005; Pappur & Khonsari, 2003; Zhou & Khonsari, 2000) to develop more comprehensive mathematical models for powder lubrication. Zhou and Khonsari (2000) considered more comprehensive constitutive equations (Lun, Savage, Jeffrey, & Chepurniy, 1984) for investigating the behaviour of powder lubricants sheared between two parallel plates. They reported that viscous dissipation plays an important role in the pseudo-energy equation. The work of Zhou and Khonsari (2000) was extended by Pappur and Khonsari (2003) to study the behaviour of an infinitely wide slider bearing. An extensive set of parametric simulations were performed, considering operating parameters such as granular size, surface roughness, load, and speed. Jang and Khonsari (2005) derived a three-dimensional model for analysing the lubrication behaviour of granular materials by correlating the pressure, pseudo-temperature, and solid volume fraction parameters.

Many attempts have been made to investigate the performance behaviour (load-carrying capacity, frictional force, coefficient of friction, and side leakage) of powder-lubricated circular-bore journal bearings using numerical and experimental approaches. During the passage of time, however, with running of the rotor, the circular bore of the journal bearing is modified to an elliptical shape, as a result of wear, misalignment, and deformation issues. Exploring the static and dynamic performance behaviour of elliptical-bore journal bearings lubricated with granular particles is therefore an essential task from a practical point of view. Moreover, for developing an understanding of the dynamic behaviour of rotors supported on powder-lubricated bearings, the evaluation of bearing coefficients is necessary. These coefficients are needed to calculate the critical speeds of rotors to examine their stability against self-excited vibrations. The objective of this study was therefore to highlight the performance behaviour and stability characteristics of elliptical-bore journal bearings lubricated with granular particles of two different sizes (1 and 2 μm). The load-carrying capacity, side leakage, friction coefficient, and stability parameters were investigated.

Mathematical model

This section outlines the mathematical model employed in the investigation. A schematic diagram of the journal bearing with its coordinate system is illustrated in Fig. 1. The orientation of the elliptical bore with respect to the load line is indicated.

Governing equations

The relation for an elliptical-bore radius (R_b) is expressed as follows (refer to Fig. 1):

$$R_b = R_{min}\sin^2(\theta - \delta) + R_{max}\cos^2(\theta - \delta). \tag{1}$$