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Free boundary of lubricant film in ferrofluid journal bearings

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Abstract

The growing interest in ferrofluid bearings is caused by their excellent self-sealing ability. The understanding of behaviour of ferrofluid film boundary adjacent to ambient air is crucial for the proper design of the sealing unit of ferrofluid bearings. This paper is the first attempt to predict the shape of a ferrofluid free boundary in the presence of a static load and magnetic field. Analysis involves simultaneous integration of the Reynolds equation and the free boundary equation using perturbation technique with respect to shaft eccentricity. Magnetic field is shown to flatten ferrofluid free boundaries as well as to reduce cavitation region; both effects diminishing lubricant leakage.

Keywords: Ferrofluids; Hydrodynamic lubrication; Journal bearings

1. Introduction

Ferrofluid dynamic bearings have a great potential of application in precision equipment such as spindles of hard disk drives, scanners, inertia wheels of mini-satellites, gyroscopes. They combine all advantages of the fluid dynamic bearings (high stiffness, excellent damping of vibrations at high speeds, low noise level) and the self-sealing ability of a ferrofluid lubricant. At rest and at low speed operation a ferrofluid lubricant is retained in the bearing clearance by a permanent magnet. This magnet prevents ferrofluid leakage, so, any other solid or capillary seals are unnecessary. At high speed operation ferrofluid is usually sealed by a pumping action of herringbone-like grooves cut on a bearing surface. Ferrofluid, itself, is a colloidal solution of magnetic nanoparticles in a carrier fluid [1], such as lubricating oil. These particles are 3–4 orders of magnitude smaller than a bearing clearance, so they are not abrasive. Furthermore, they do not sediment and are not aggregated under magnetic field.

The pioneering work in the domain of ferrofluid lubrication has been done by Tarapov [2]. He considered a plain journal bearing lubricated with ferrofluid and subjected to a non-uniform magnetic field, and showed that the bearing load capacity increases in the magnetic field due to magnetic levitation force acting on a rotating shaft. Since then, numerous scientific researches concerning ferrofluid dynamic bearings have been done. Static and dynamic characteristics of these bearings have been studied theoretically in [3–11]. Recent trends in the domain of ferrofluid lubrication are oriented towards design of closed–to market ferrofluid bearings for hard disk drives or other high-speed minirotors. Some designs and characteristics of novel ferrofluid bearings are discussed in the papers [12–15], the review on ferrofluid bearing designs and applications being given by Ochonski [16].

It appears that the ferrofluid self-sealing effect works against ferrofluid leakage caused by gravity, centrifugal forces, shocks and vibrations, as indicated in [13,16]. The ferrofluid seal seems also to prevent leakage caused by hydrodynamic pressure, when in high pressure regions the lubricant film tends to go outward of the bearing clearance. This sealing effect is found to be effective at low speed operations (see [7,13]). Nature of such magnetic field effect on decrease in leakage caused by hydrodynamic pressure is not yet completely clear. It could seem and it is sometimes stated in literature that the sealing magnetic pressure gradient can equilibrate the hydrodynamic pressure gradient on the fluid film lateral boundary and therefore

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Nomenclature

$A = (\mu_0 M_S H_0)/(\eta\omega R^2/C^2)$, and $A_1 = A \cdot h_1$, $A_2 = A \cdot h_2$ magnetic field parameters
a parameter of the magnetic field distribution
C bearing clearance
D_0, D_1, D_2 coefficients in pressure distribution
E axial boundary extension
e dimensional shaft eccentricity
H magnetic field intensity
H_0 magnetic field intensity at bearing centreline $z = 0$
h ferrofluid film thickness
h_1, h_2 shape factors of the magnetic field distribution
L bearing length
M ferrofluid magnetization
M_S ferrofluid saturation magnetization
P reduced pressure
P_0, P_1, P_2 zero, 1st and 2nd order terms of pressure
p total pressure (including magnetic pressure)
p_0 dimensional ambient pressure
p_{cav} cavitation pressure
Q leakage rate
R shaft radius
v_z, v_θ axial and azimuthal velocities of the free boundary
z axial coordinate

Greek symbols

Δ,δ dimensional and dimensionless cavitation parameters
$\varepsilon = e/C$ dimensionless shaft eccentricity
ϕ_1, ϕ_2, ψ_1, ψ_2 coefficients in the equation of the free boundary
η ferrofluid dynamic viscosity
$\lambda = L/(2R)$ bearing length parameter
$\mu_0 = 4\pi \times 10^{-7}$ Henry/m magnetic permeability of vacuum
θ polar angle
θ^* polar angle corresponding to the peak the free boundary shape
θ_0, θ_1 coefficients in equations for θ^* and E
π_0 dimensionless ambient pressure
ω shaft angular speed
$\xi(\theta)$ free boundary shape (its axial coordinate as function of its polar coordinate)
ξ_1, ξ_2 1st and 2nd order terms of free boundary shape

cancel the leakage rate. But, as we shall see in Section 2 of this paper, the magnetic field does not influence at all the leakage rate of ferrofluid, if no cavitation occurs, but does only in presence of cavitation. Osman with colleagues [10] have considered a ferrofluid journal bearing subjected to cavitation condition and shown theoretically that a magnetic field decreases the leakage rate. They explain it by intense inward flows of a ferrofluid lubricant towards cavitation region, but the nature of this effect is not still completely clear.

In all known works dealing with a problem of ferrofluid leakage, a standard fluid film configuration was considered, like shown in Fig. 1a. In this configuration, the ferrofluid film extends from one lateral side of the bearing to another side having straight fixed boundaries. This configuration is usually realized in fluid dynamic bearings with feeding groove, which delivers continuously lubricant in a bearing gap and therefore compensates leakage under hydrodynamic pressure. Ferrofluid bearings do not usually have any feeding system, because they are designed as self-sealed bearings. In these bearings the ferrofluid film does not occupy all the clearance, but is retained in the central part between two lateral sides (Fig. 1b). Under external load the rotating shaft displaces from the central position inside a bearing sleeve that generates high pressure zones in a converging part of a ferrofluid film and low pressure zones in a divergent part. So, in high pressure zones, the ferrofluid will tend to flow outside, towards the lateral bearing sides, and in the low pressure zones—to flow inside. It means that lateral ferrofluid boundaries are not fixed but are free to move and to bend, that implies the term "free boundary". Under certain conditions, propagation of the ferrofluid boundary can stop and the lubricant film will take stationary irregular shape, as shown schematically in Fig. 1b. The shape of the free boundary is determined by two following conditions: (1) ferrofluid velocity normal to the boundary is zero, and (2) mass conservation of the ferrofluid in the lubricant film. If the hydrodynamic pressure is too high, the free boundary will reach the lateral sides of the bearing and leak outside. What is the magnetic field effect on such a propagation of the ferrofluid free boundary? Does the magnetic field reduce the outward extension of the ferrofluid film? These are the key questions that we try to answer in the present paper.

The problem of free boundary shape in fluid film bearings lubricated with non-magnetic fluids have been studied theoretically in [17,18] for spiral groove journal bearings, and in [19] for spherical and conical spiral groove bearings. In their papers the authors find a bell-like shape of the free boundary, they show that the boundary becomes more curved with growth in eccentricity (and in external load) and analyse the influence of groove geometry on the outward extension of a fluid film. To our knowledge, no results are given in literature for the fluid film lateral boundary in plain journal bearings, neither for ferrofluid bearings. Most of the free boundary problems reported in literature deal with the shape of cavitation region (see, for instance, [20,21]), rather than with lateral free boundary of lubricant film.