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A novel view on lubricant flow undergoing cavitation in sintered journal bearings

Bernhard Scheichl [a,b,*,1], Ioana Adina Neacşu [a,1], Alfred Kluwick [b]

[a] AC²T research GmbH, Viktor-Kaplan-Straße 2C, A-2700 Wiener Neustadt, Lower Austria, Austria
[b] Institute of Fluid Mechanics and Heat Transfer, Vienna University of Technology, Tower BA/E322, Getreidemarkt 9, A-1060 Vienna, Austria

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ABSTRACT

A new rational formulation of the cavitation phenomenon occurring in porous journal bearings in the regime of fully hydrodynamic lubrication is presented. The suitably extended form of the Reynolds equation is coupled with the semi-phenomenological Darcy's law so as to yield a proper description of the combined flow through the lubrication gap and the porous (sintered) seat, respectively. It is found that the initially unknown boundaries of cavitation give inevitably rise to gradual steepenings of the pressure gradients and the saturation of the lubricant at recondensation that finally form up to localised discontinuities. Hence, it is focussed on both theoretical foundations and an elaborate numerical investigation of the resultant lubrication problem. In order to determine the limits of applicability of this approach, specific investigations aim at evaluating the extreme cases of relatively low and high bearing loads, i.e. $\varepsilon \to 0$ and $\varepsilon \to 1\_$ where $\varepsilon$is the eccentricity ratio, and very long/short as well as highly porous/(almost) massive bearings. Here the effort is seen to be reduced by considering appropriate distinguished limits. The results include values of the friction coefficient obtained for various configurations and, most interestingly, point to a threshold value of ε above which the loss of numerical solutions indicates the loss of steady-state operation of the bearing. A first validation by in-house experiments proves satisfactory.

1. Introduction

When the friction forces between parts in relative motion have to be minimal, a thin layer of either oil, grease or solid particles is commonly introduced between the parts, as to avoid the undesired surface contact. In journal (i.e. slide) bearings this separation is accomplished by the action of hydrodynamic lubrication, where a fluid film that carries the load imposed on the bearing is formed as a result of the rotation of the eccentrically displaced journal. In conventional or massive bearings, this mechanism is maintained steadily through a localised supply of the lubricant, i.e. external reservoir of lubricant. In contrast, here we are interested in mass-preserving journal bearings, also referred to as self-lubricated bearings, which operate in a similar manner as classical journal bearings. The fundamental difference is the porous (sintered) seat: its impregnation with lubricant is necessary only once (at the beginning of the lifecycle of the bearing).

The literature on this subject is enormous and constantly growing, thereby expressing the thriving interest and demand for self-lubricated bearings by engineers. Manufacturing and application of porous journal bearings motivating much research in this direction, pondered by Kumar [1]. Unfortunately, an overview covering the most important developments in the reliable computational prediction of the behaviour of such systems and the underlying theoretical approaches is not existing, at least to the authors' knowledge. Therefore, in the following we just cite the publications considered most relevant and/or pioneering in terms of originality and classical but do not claim that this list is exhaustive in nature. The ultimate goal of this study is gaining a deepened understanding of the flow behaviour in self-lubricated bearings and hence a satisfactorily accurate prediction of their steady-state operation.

We therefore focus at a most simple self-consistent description of the physical mechanisms at play; shortcomings arising from non-rational modelling of the physics involved (though at a higher level of complexity) are avoided. To this end, some new/established theoretical aspects are in turn highlighted/revisited in greater breadth and depth as usually in the corresponding tribological literature. In this spirit, the present paper and fully numerical studies on the subject complement. Regarding the latter, the very recent one by Balasoiu et al. [2] serves as a useful example: they adopt the full governing equations for multiphase flow, supplemented with advanced semi-

* Corresponding author at: AC²T research GmbH, Viktor-Kaplan-Straße 2C, A-2700 Wiener Neustadt, Lower Austria, Austria.
Tel.: +43 2622 81600 158; fax: +43 2622 81600 99.
E-mail addresses: scheichl@ac2t.at, b.scheichl@tuwien.ac.at (B. Scheichl).

[1] See talk at the 39th Leeds–Lyon Symposium on Tribology (Great Challenges in Tribology), Leeds Trinity University College (Leeds, UK), 4–7 Sept. 2012.

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phenomenological closures. In contrast, the numerical analysis performed here and forming the central part of our study (Section 4)

- rests upon a careful, critical re-examination of the underlying physics on the different scales involved (Section 1),
- a thorough formulation of the lubrication problem involving the minimum number of non-dimensional groups (Section 2), which enables
- (as a side issue) a rigorous though preliminary analytical study dealing with several theoretical aspects of the problem not addressed previously (Section 3) and including
- (as an exciting novelty) the inevitable event of spontaneous recondensation, i.e. of saturation jumps, in steady-state operation of self-lubricated bearings (due to their periodic geometry),
- brings in a new efficient numerical strategy that copes with cavitation of an incompressible lubricant involving that phenomenon and tackles directly the steady-state operation (Section 4.1),
- eventually allows for a systematic parameter study and prediction of the bearing performance (Section 4.2),
- attended by an experimental validation (Section 4.3).

1.1. Self-lubrication of porous bearings

The basic principle behind the functioning of these type of bearings is that a porous network acts as a reservoir of the fluid so as to achieving a cohesive lubricant film In the loaded part of the bearing the lubricant is pushed into the porous channels of the seat, while the flow through the unloaded part contributes in refilling this lubrication gap [3]. Therefore, the main factor which influences the capability of storing and releasing lubricant is porosity, defined as the ratio between the void fraction and the total volume of the porous bearing. Common values for porosity lie between 20% and 35%, depending on the type of application (e.g. requiring a minimum of mechanical strength of the seat).

The porous network forming the seat consists of highly contorted and interconnected microscopic channels. The description of the creeping flow percolating through this entangled network on a macroscopic length scale, represented by the local distance $\tilde{r}$ from the centre of the seat, most commonly is based upon Darcy's law. It can be derived formally from the Stokes-flow assumption on the microscopic scale of a fluid (lubricant) with uniform dynamic viscosity $\tilde{\eta}$ and density by means of scale separation involving a proper homogenisation (averaging) process: we refer to the seminal papers [4–6] (and references therein). The thereby resulting quantities comprise the local porosity or void fraction ϕ of the sinter, the local flow velocity $\tilde{\boldsymbol{v}}$, and the difference $\tilde{p}$ between the local pressure and that in the (gaseous) environment of the bearing, $\tilde{p}_a$, taken as uniform:

$$\phi(\tilde{\boldsymbol{x}}) := \frac{1}{\tilde{V}_{\mathcal{S}}} \int_{\mathcal{S}} \Sigma(\tilde{\boldsymbol{x}}')\,\mathrm{d}\tilde{V}_{\mathcal{S}}, \; [\tilde{\boldsymbol{v}}, \tilde{p}](\tilde{\boldsymbol{x}}) := \frac{1}{\phi(\tilde{\boldsymbol{x}})\tilde{V}_{\mathcal{S}}} \int_{\mathcal{S}} [\tilde{\boldsymbol{v}}', \tilde{p}'](\tilde{\boldsymbol{x}}', \tilde{\boldsymbol{x}})\Sigma(\tilde{\boldsymbol{x}}')\,\mathrm{d}\tilde{V}_{\mathcal{S}},$$

$$\tilde{\boldsymbol{x}}' := \frac{\tilde{\boldsymbol{x}}}{\sigma} \quad \text{for} \quad \sigma \ll \frac{\tilde{V}_{\mathcal{S}}(\sigma)^{1/3}}{\tilde{r}} \ll 1. \tag{1}$$

Herein primes indicate the quantities governing the microscopic flow process; the dependences on the macroscopic and microscopic space variables $\tilde{\boldsymbol{x}}$, $\tilde{\boldsymbol{x}}'$ having the reference lengths $\tilde{r}$ and the local one $\sigma\tilde{r}$ are stated explicitly. The first accounts for the variation of the flow due to the conditions holding at the surface of the porous network, the second introduces the ratio of the single length scale characteristic of the micro-structure of the network and $\tilde{r}$.

Integration in (1) is carried out locally over the fraction of space $\mathcal{S}$ exhibiting a volume $V_{\mathcal{S}}$, defining an intermediate scale in the formal limit $\sigma \to 0$ associated with the homogenisation process. Accordingly, the characteristic or indicator function Σ in (1) assumes the values 1 or 0 depending on whether fluid is present at the position $\tilde{\boldsymbol{x}}$ or not. Hence, under the neglect of capillary effects as presumed subsequently, isolated cavities (lacking fluid) constitute the "foam" contribution to the porous network whereas the porosity ϕ as defined by (1) forms the complementary "sponge".

On the macroscopic scale, the inversion of the Stokes equation finally shows that in Darcy's law,

$$\tilde{\eta}\phi\tilde{\boldsymbol{v}} = -\tilde{\boldsymbol{\Phi}} \cdot \nabla_{\tilde{\boldsymbol{x}}}\tilde{p}, \tag{2}$$

now correctly including the porosity, the symmetric permeability tensor $\tilde{\boldsymbol{\Phi}}$ arises from the homogenisation process. Under the assumptions made above, this geometrical quantity is a functional of ϕ solely. However, due to the evidently practical (numerical) inaccessibility of the $\tilde{\boldsymbol{\Phi}}$-$\phi$-relationship it is the permeability rather than (2) one should term phenomenological. The scalar porosity is apparently much more susceptible to measurement than the permeability, i.e. the components of $\tilde{\boldsymbol{\Phi}}$, but this is of limited benefit in view of a reliable modelling of $\tilde{\boldsymbol{\Phi}}$. Nevertheless, a number of semi-empirical expressions and theories were proposed, among which the one advanced by Kozeny [7], here see also the classical textbook by Scheidegger [8], remains the most widely appreciated. His approach is based on the rough assumption that the porous medium is equivalent to a set of quite slender circular channels exhibiting varying area cross-sections embedded in a rigid matrix. The equation he derived expresses the dependence of the permeability on the specific overall surface area of the porous medium. However, many subsequent experimental studies, cf. [8], pp. 137–144, show severe deviations from the theoretical results. For this reason, formulating the individual components of $\tilde{\boldsymbol{\Phi}}$ and assigning the missing values to the arising parameters is still merely empirical at present; their reliable measurements are challenging. In many important cases, ϕ and, in turn, $\tilde{\boldsymbol{\Phi}}$ can be taken as homogeneous, i.e. constant (isopermeable material), and/or Darcy's law (2) as a locally orthotropic constitutive relationship. Then $\tilde{\boldsymbol{\Phi}}$ is represented only by its three diagonal components. In the commonly assumed case of a locally perfectly isotropic tensor $\tilde{\boldsymbol{\Phi}}$ it is even purely spherical and determined by the single scalar $\tilde{\Phi} = \mathrm{tr}(\tilde{\boldsymbol{\Phi}})/3$. In the most basic case of homogeneous isotropy of the permeability this scalar is again a constant.

We emphasise that the extensions of (2) by Brinkman [9] (accounting for a smooth transition of the homogenised towards the cohesive flow adjacent to a porous surface) and in terms of the well-known Darcy–Brinkman–Forchheimer law (accounting for inertial effects) are definitely phenomenological if not inconsistent at all with the basic assumption of creeping flow. This motivates us to use Darcy's classical law in the form stated by (2). Applying the continuity equation $\nabla_{\tilde{\boldsymbol{x}}} \cdot (\phi\tilde{\boldsymbol{v}}) = 0$ ensuing from the homogenisation process to (2) finally yields the equation

$$\nabla_{\tilde{\boldsymbol{x}}} \cdot \left(\tilde{\boldsymbol{\Phi}} \cdot \nabla_{\tilde{\boldsymbol{x}}}\tilde{p}\right) = 0 \tag{3}$$

governing the macroscopic or Darcy pressure. In case of isotropy, (3) reduces to Laplace's equation.

1.2. Cavitation in lubrication

The hydrodynamic pressure generated in the fluid film between a rotating shaft and a bearing was first considered rigorously by Osborne Reynolds in 1886. For what follows, the classical prerequisites of lubrication theory are adopted: a Newtonian lubricant in laminar flow where inertial forces are negligibly small compared to the viscous ones and a relatively thin lubrication gap. Consequently, from neglecting the inertia terms in the leading thin-layer approximation of the Navier–Stokes equations the Couette–Poiseuille velocity profile ensues; substituting this approximation for $\tilde{\boldsymbol{v}}$ in