RESEARCH GRANT REPORT

Project title: **"A study of lubrication mechanisms using 2-phase fluids with porous bearing materials"**

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Introduction

The basic principle under examination in this project may have applications in many common engineering machine elements where normal bearing load variations are present; for example, in crank-shaft and main bearing applications or cam-follower applications in internal-combustion engines. However, an area of particular importance and interest to the researcher exists in rolling-element bearings, where the rolling elements undergo oscillating forces within the cage pockets. Thus, this particular area/geometric configuration was chosen as the basis of the theoretical research in order to examine the concept.

Ball and roller bearings are a major Machine Element in industrial applications. The life and efficiency of these elements depend on the effectiveness of their lubrication, especially in high-load and/or high-speed applications. Friction and wear are greatly reduced when there is a continuous film separating two cooperating surfaces, like in the case of a ball and a ring in a ball bearing. Therefore, it is vital that adequate quantity of lubricant be always supplied in the area that mostly needs it, to produce a film of such thickness, that it is able to sufficiently separate cooperating surfaces and minimize their relative friction by eliminating the number of roughness asperities in contact. However, even if lubricant is supplied at relatively large quantities, there are two problems:

(1) load fluctuations, as in the form of a sudden increase or in the form of "noise", and
(2) lubricant replenishment of the contact. This means that when a rolling element on its raceway passes through a particular area, it displaces lubricant that was residing in that area, so that when the following rolling element comes through, there is not enough lubricant left to produce the necessary film, the latter situation known as "starved lubrication".

A method to deal with problem (1) and (2) above could be to use porous bearings. These bearings can store lubricant in their pores and release it when needed. The great advantage is that lubricant is released exactly where needed, exactly when needed. However, the great disadvantage is that porous materials are relatively soft and cannot withstand relatively high loads, a case often met in bearing applications. Therefore, porous bearings cannot be generally applied.

To combine the advantages of porous bearings and common (non-porous) bearings, a new concept was conceived and put into test in the authors' laboratories. The concept has two parts.

(a) Bearing rings are to be made of homogeneous materials, in other words non-porous. Therefore, their load-carrying capacity will remain intact, compared to the porous bearing case. However, the bearing cage is to be made of a porous material, and therefore will act as a lubricant tank, ready to release lubricant following an increase of load between a rolling element and the cage.
(b) Additionally, small and soft particles in the form of very thin disks (thickness in the order of the anticipated film thickness between the rolling elements and the rings, assuming EHD lubrication) are to be freely mixed with the lubricant and circulated in the bearing. These tiny particles are to act as one-way valves, allowing for lubricant to be sucked from the free surface of the cage and then to be released in the contact interface between the rolling element and the cage, and transferred - through the

rolling element's rotational motion - to the area needed, which is the contact interface between a rolling element and a ring.

The concept may also work in the case where the main bearing surfaces are of a porous material, although in a slightly different manner. This report summarizes the way the concept works through a theoretical model as well as through some basic experimentation using a simple rig manufactured in the authors' laboratories.

Theoretical work

The mechanics of porous solids, saturated by a fluid mixture, was first tackled to a serious extent by Biot in the 1940s. Since then, his theory gained much acceptance and is still used in relevant research areas. The computer model the author has constructed is based on those initial publications of Biot (see references) which are pronounced for their clarity and usefulness. More specifically, using Biot's 1941 publication, which sets the foundation of a general theory of 3-dimensional consolidation for porous isotropic solids, the present author constructed a model to suit the particular case of a porous slab, which is being subjected to a fluctuating load, due to a ball oscillating on the upper surface of the slab, as shown in Fig. 1 below.

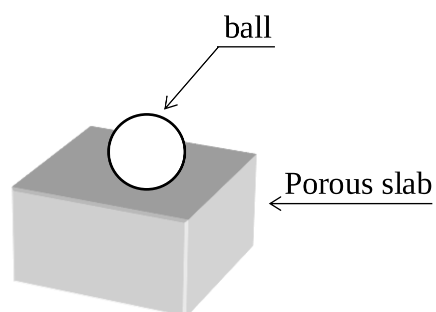

Fig. 1
Theoretical model.

The slab could be further extended in the lateral directions (not shown in Fig. 1) as if it were part of a bearing cage. The upper surface of the slab is thought to be the inner surface of a cage pocket, intended to accommodate a rotating ball - part of the bearing assembly. Lubricant is assumed to adhere to both the upper and lower surface of the slab. The lubricant mixture is a 2-phase fluid, consisting of a liquid phase and a solid phase, the solid phase being small particles (platelets) engineered to have a mean diameter greater than the average diameter of a typical slab pore. Therefore, platelets cannot enter pores, but can close them, obstructing liquid flow into them during a decrease of the load of the ball. The author's model is based on the following assumptions.

(1) The slab is considered isotropic.
(2) The slab is completely saturated with incompressible fluid at any time.
(3) Darcy's law can be used to describe the flow inside the slab.
(4) Any pores which lie inside the Hertz circle of the contact between the ball and the upper surface at any time are assumed covered by platelets and, thus, are impervious.
(5) The pores are scattered on the upper and lower surface of the slab in a random

manner.

(6) The particles are free to move in a random way. Thus, their location on the slab surfaces changes with time in a random manner.

Based on the previous assumptions and using Biot's fundamental equations of 3-d consolidation (see [1]), the author has constructed the following partial differential equation, from which the fluid pressure in the pores can be calculated at any time, anywhere in the slab:

$$\nabla^2\sigma = \frac{E}{9\cdot(1-2\cdot\nu)\cdot K}\cdot\left[\frac{\partial}{\partial t}\left(\sigma_{x_{mech}}+\sigma_{y_{mech}}+\sigma_{z_{mech}}\right)+3\cdot\frac{\partial\sigma}{\partial t}\right]$$

where σ is the fluid pressure inside the pores of the slab, E is the modulus of elasticity of the slab's solid material, ν is the Poisson ratio of the slab's solid material, K is the coefficient of permeability of the slab, t is for time, and $\sigma_{x_{mech}}$, $\sigma_{y_{mech}}$, $\sigma_{z_{mech}}$ are the mechanical stresses in three principal directions x, y and z respectively, perpendicular to the faces of the slab. By knowing the fluid pressure space gradient on a surface pore, fluid speeds can easily be found through Darcy's basic equation. Thus, for given pore diameter, fluid flow rate can easily be found on both the upper and lower surface of the slab.

A general study of the problem allows for the following variables (parameters):
(1) The dimensions of the slab and the ball.
(2) The mechanical properties of the solids and the lubricant.
(3) The number and density of surface pores (porosity).
(4) The average pore diameter.
(5) The ball load as a function of time.
(6) The time to study the lubrication of the contact.

Despite the assumptions used, the theoretical model has still a complex mathematical part and this complexity is transferred to the computer program written for this model. The latter can tackle a parametric study with the parameters as listed previously, but consumes excessive processing time for an adequate study that can be as high as several days of continuous CPU time of a Pentium-II processor, running at 266 MHz, like for example when the number of surface pores is in excess of 1,000.

The ball's load-time function used is of the form: $P(t) = P_0 + P_1\cdot\cos(P_2\cdot t) + P_3\cdot\delta(t)$ where P_0, P_1, P_2 and P_3 are constants (parameters) and δ(t) is a perturbation, used to simulate a sudden load increase or even noise of any frequency. If term δ(t) is omitted (by setting $P_3 = 0$), the load-time function is a smooth sinusoidal distribution. Both cases of smooth and "rough" loading were studied and the results are analyzed below.

Example 1: smooth loading, $P(t) = P_0 + P_1\cdot\cos(P_2\cdot t)$

In this case, the concept is found to work. This means that - as time increases - there is an overall replenishment of lubricant on the upper surface of the slab and in the vicinity of the contact with the ball. The additional lubricant is coming from inside the slab and has been sucked mainly from the lower surface pores. An example of the predicted results of the model is shown in Fig. 2. The thick curves in the aforementioned figure refer to lubricant quantity on the upper surface of the slab, where the contact with the ball takes place. The curve is rough in its lower part due to assumption (6) (particles are free to move in a random manner, which means that the number of pores blocked during a load decrease varies with time). The thick fitting line tends asymptotically to a positive value (constant lubricant flow), which, by definition, means that lubricant is continuously added on the upper surface of the slab, thus improving the lubrication of the contact by increasing the oil bath thickness. Similarly, the thin curves in Fig. 2 refer to lubricant exchanged through the pores of the lower surface of the slab. This curve is smooth because the lower surface pores are assumed open all the time.

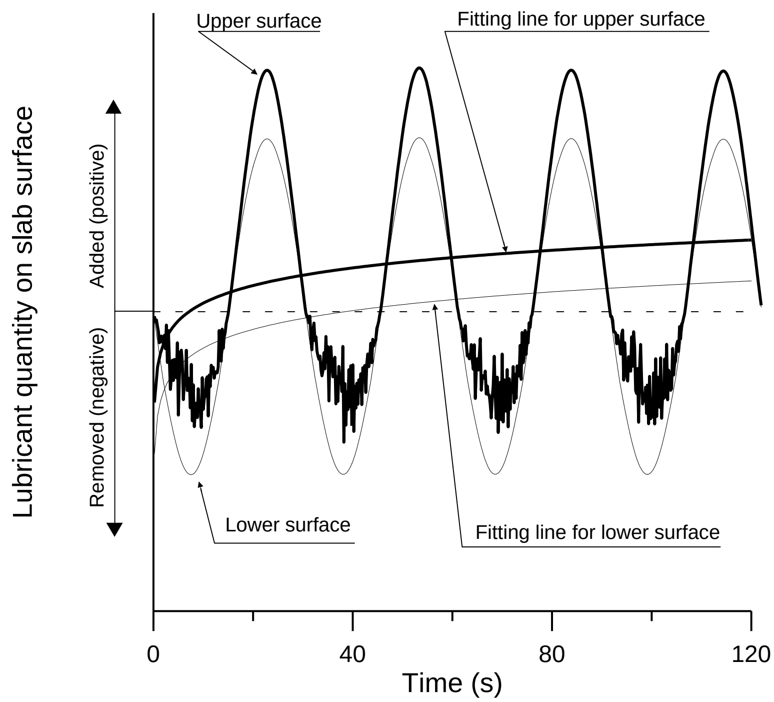

Fig. 2

Lubricant quantity versus time, on the upper and lower surface of the slab.
Load time function: $P(t) = 10 + 5 \cdot \cos(-0.2 \cdot t)$ [N]

The problem is that the thin fitting line tends asymptotically to a positive value, which means that, eventually, the slab will become starved, collecting air bubbles inside the pores instead of lubricant. The author had a number of ideas to overcome this difficulty, all of which concentrate on the fact that, for long-term lubrication enhancement of the contact, the lower surface pores should not be allowed to expel lubricant. This might be achieved for example by adding a very thin solid layer to the lower slab surface, having pre-engineered tiny holes, which accommodate one-way valves, like in Fig. 3.

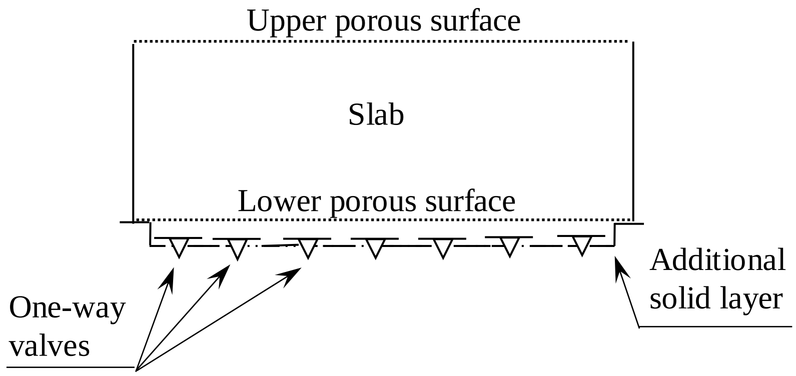

Fig. 3
A possible way to avoid lubricant leakage from the lower slab surface.

Other assemblies have also been considered and it is a matter of manufacturing feasibility to decide which one is to be finally chosen.

There are three advantages in preventing lubricant leakage from the lower slab surface.
(a) The slab is less likely to become eventually starved.
(b) More lubricant is expelled through the pores of the upper slab surface during a load increase.
(c) The slab becomes more rigid (lubricant is assumed incompressible).

Example 2: "rough" loading, $P(t) = P_0 + P_1 \cdot \cos(P_2 \cdot t) + P_3 \cdot \delta(t)$, ($P_3 \neq 0$)
If the noise term [$P_3 \cdot \delta(t)$] is of relatively high magnitude and high frequency ($\delta(t)$ changing value at each time step, i.e. $\delta(t) \neq 0 \;\; \forall \;\; t \geq 0$), the concept studied in this report doesn't seem to work. This happens because the lower slab surface tends to expel lubricant constantly, without intervals of replenishment. The latter eventually leads to a starved slab and poorer lubrication of the contact, compared with the case of a non-porous slab.

On the other hand, when the load perturbation has relatively low frequency ($\delta(t) = 0$ for relatively large periods of time) and small magnitude compared to the maximum "smooth" load (load with the perturbation term), the concept works as in the case of the smooth load function quoted earlier in this report.

Experimental work

The experimental part of the project was performed by a 3M student (see [8]) in the author's laboratories. The objective was the construction of a simple rig to study the concept of the present work. For reasons of low cost and time constraints, an essentially static rig was constructed, designed to operate on a macro scale (large particles and pores). The basic mechanical principal of the rig was formed by a flat-ended, 40 mm (in diameter) piston arrangement, acting against porous disks in the presence of a lubricant seeded with platelet-like particles. Photographs of the rig can be seen in [8], available from the author's section. The rig is said to be essentially static because the piston oscillates very slowly, with a vertical speed of 1 mm/min.

The results of the experiments suggest that the concept works indeed in the case of a static rig, operating on a macro-scale level. The analysis pointed out that the concept is improved for a greater concentration of the secondary particulate phase in the lubricant, and works best for an even distribution of particles over a porous surface. Because of the static rig (which actually means that the load is changing at a very slow rate), no conclusion could be drawn about the effect of porosity on the results.

Conclusions

The present work has shown theoretically that the concept of enhancing lubrication of bearings by using a secondary particulate phase in the lubricant and porous cages works indeed on a micro level under dynamic (realistic) conditions, but only for a limited time. In order to achieve long term lubrication improvement, it was suggested that the porous surfaces were engineered in a special way, discussed earlier in this report, to avoid lubricant starvation after some time of operation. The concept was found to encounter significant problems in the case there is a lot of relatively high magnitude and high frequency noise in the loading of the system, but this case is not often met in real cases. One possible problem, not studied in this work, is the likelihood of particle accumulation in the contact of rolling elements, which could lead to lubricant starvation and increased wear.

On the other hand, preliminary experimental work, using a simple macro-scale rig under static conditions (as opposed to the actual dynamic conditions found in a real system) showed again that the concept works.

The findings of this project can stimulate further research, and there is a possibility of a future patent or at least a publication on this subject.

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