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INVESTIGATION OF THE EFFECT OF SURFACE TEXTURING IN HYDRODYNAMIC SLIDING CONTACTS

Polach P.*, Smolík L., Byrtus M.***, Hajžman M.†**

Abstract: *Hydrodynamic lubrication is an effective method for connecting various relatively moving structural components in engines, rotors, manipulators, and other systems. Surface texturing can enhance the performance of such contacts. Initially, a theoretical framework for modeling textured surfaces of journal bearings is introduced, which is then employed to analyze the dynamic behavior of rotors. Additionally, a pin-on-disc approach for determining the properties of a lubricated textured surface is presented. The objective of utilizing the pin-on-disc method is to enhance computational models of lubricated textured pins by comparing experimental measurements with numerical simulation results. The knowledge gained can be applied to optimize parameters in computational models of hydrodynamic contact for textured surfaces in various applications, such as the model presented for journal bearings.*

Keywords: Hydrodynamic lubrication, textured surface, journal bearing, pin-on-disc method.

1. Introduction

Hydrodynamic sliding contacts are often found in various mechanical components. These are, for example, journal and thrust bearings, piston rings, and thrust washers and seals. Low friction, high load-carrying capacity, and long service life are the main goals in developing these contacts. One of the most important directions of development is surface texturing.

A large number of studies have been written and have reported a positive contribution of surface texturing since the 1960s when the first evidence of positive effect was found by Hamilton et al. (1966). There are various positive contributions of targeted surface modifications. Generally speaking, it is believed that surface dimples can help to supply the contact with lubricant, entrap wear particles, and reduce the direct contact area and level of adhesion. In a hydrodynamic regime, dimples can increase load-carrying capacity thanks to local cavitation with asymmetric pressure distribution or inertia-related effects (Gropper et al., 2012; Lu and Wood, 2020).

As indicated, surface texturing is one important approach to improving the tribological performance of hydrodynamic contacts. A certain problem is that the effect of the texture strongly depends on a large number of contacts and operating parameters concerning the mode in which the lubricated contact works. There is also texture coupling to wall slip, cavitation, thermal effects, etc. It should be noted that a positive effect under certain conditions can therefore become detrimental under other conditions.

Based on the comparison of experimental and simulation results in the field of textured journal bearings (which we mainly focus on), despite the careful construction of computational models, discrepancies appear

* Assoc. Prof. Dr. Ing. Pavel Polach: New Technologies for the Information Society, European Centre of Excellence, University of West Bohemia, Univerzitní 8; 306 14, Plzeň; CZ, ppolach@ntis.zcu.cz

** Ing. Luboš Smolík, PhD.: New Technologies for the Information Society, European Centre of Excellence, University of West Bohemia, Univerzitní 8; 306 14, Plzeň; CZ, carlist@ntis.zcu.cz

*** Assoc. Prof. Ing. Miroslav Byrtus, PhD.: Department of Mechanics, Faculty of Applied Sciences, University of West Bohemia, Univerzitní 8; 306 14, Plzeň; CZ, mbyrtus@kme.zcu.cz

† Assoc. Prof. Ing. Michal Hajžman, PhD.: Department of Mechanics, Faculty of Applied Sciences, University of West Bohemia, Univerzitní 8; 306 14, Plzeň; CZ, mhajzman@kme.zcu.cz

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in the results achieved. The differences arise from the complex interplay of the above-mentioned influences on the behavior of the hydrodynamic contact. Legitimate doubts may arise regarding the quantitative experimental reproducibility of published theoretical work on fluid-induced instability, indicating the need for further research in this field. Some of the mentioned effects can be experimentally measured and computationally modeled on a simpler system than a journal bearing. The experimental laboratory pin-in-disc method offers a means to explore the tribological properties of textured hydrodynamic contact under diverse conditions. The knowledge gained from the modeling of this simpler system can subsequently be applied to the modeling of real textured journal bearings.

A theoretical approach to modeling textured surfaces for the journal bearings case is presented in Chapt. 2 of this paper. A pin-on-disc method used to determine the effect of different texture configurations on the tribological properties of the contact is presented in Chapt. 3.

2. A theoretical approach to the modeling textured surfaces for the case of journal bearings

This section presents a model appropriate for simulating the dynamics of a rotor that is supported by a textured journal bearing (see Fig. 1).

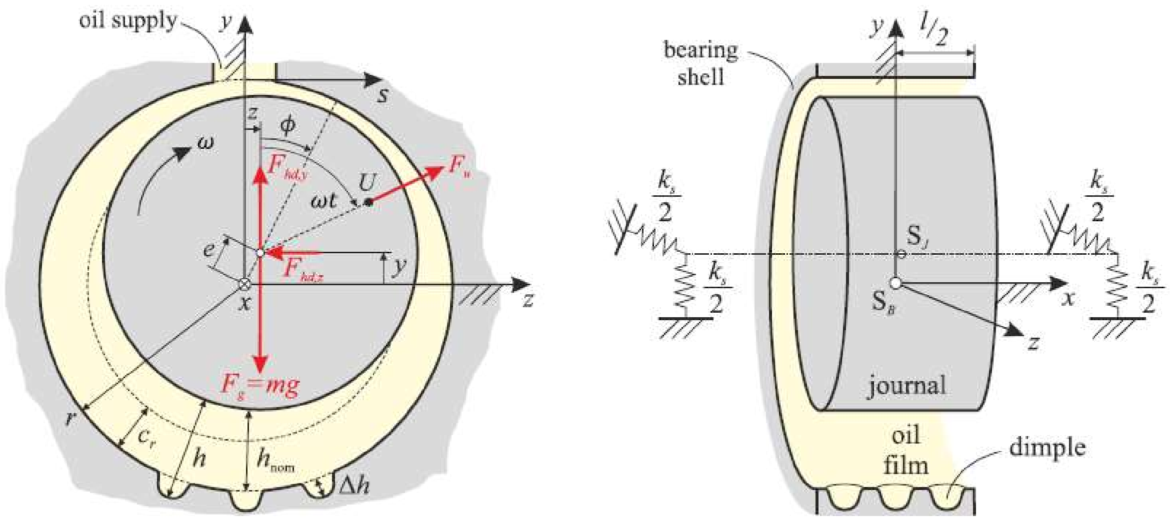

Fig. 1: The geometry of a journal bearing with a textured shell (taken from Smolík et al., 2023).

2.1. Equations of motion

It will be assumed that the mass m of the rotor is supported by a journal bearing rotating at an angular speed ω. The rotor is subjected to hydrodynamic forces, out-of-balance forces, and gravitational force. The motion of the rotor can be expressed, for instance, as shown by Smolík et al. (2023), by the equations

$$\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}\begin{bmatrix} \ddot{y}(t) \\ \ddot{z}(t) \end{bmatrix} + \begin{bmatrix} k_s & 0 \\ 0 & k_s \end{bmatrix}\begin{bmatrix} y(t) \\ z(t) \end{bmatrix} = \begin{bmatrix} U\cos(\omega t) \\ U\sin(\omega t) \end{bmatrix} + \begin{bmatrix} F_{\mathrm{hd},y}(\dot{y},\dot{z},y,z) \\ F_{\mathrm{hd},z}(\dot{y},\dot{z},y,z) \end{bmatrix} + \begin{bmatrix} -mg \\ 0 \end{bmatrix} \tag{1}$$

where k_s is the artificial stiffness of the system, which includes the stiffness of auxiliary bearings, shaft, and shaft coupling to the drive, U is the static unbalance of the rotor, g is the gravitational acceleration, $\ddot{y}(t)$, $\ddot{z}(t)$ are the accelerations in the direction of the respective axes and $F_{\mathrm{hd},y}(\dot{y},\dot{z},y,z)$, $F_{\mathrm{hd},z}(\dot{y},\dot{z},y,z)$ are components of the hydrodynamic forces (see Sect. 2.2).

Equations of motion (1) are the same for rotors with textured and non-textured bearings. The influence of the texture is reflected only when hydrodynamic forces are determined (see Sect. 2.2).

Equations of motion are usually solved by one of the numerical integration methods.

2.2. Hydrodynamic forces

The hydrodynamic force acting in the journal bearing is determined by the hydrodynamic pressure $p = p(s,x,t)$ developed within the oil film. The lateral hydrodynamic force acting on the rotor is obtained by integrating p over the bearing surface

$$\begin{bmatrix} F_{\mathrm{hd},y}(\dot{y},\dot{z},y,z) \\ F_{\mathrm{hd},z}(\dot{y},\dot{z},y,z) \end{bmatrix} = -\int_{-l/2}^{l/2}\int_{0}^{2\pi} p(s,x,t)\begin{bmatrix} \cos\left(\frac{s}{r}\right) \\ \sin\left(\frac{s}{r}\right) \end{bmatrix} \mathrm{d}s\mathrm{d}x, \tag{2}$$

where s and x are circumferential and axial coordinates relative to the bearing shell, r is the radius of the bearing shell and l is the length of the bearing (see Fig. 1).

The most common approaches to simulate hydrodynamic lubrication in textured journal bearings depend on a numerical solution of the Reynolds equation (Gropper et al., 2012) which governs the pressure distribution $p = p(s,x,t)$ in a thin two-dimensional fluid film. The precise formulation of the equation that governs the pressure distribution in the oil film relies on simplifying assumptions. In this context, it is assumed that the oil film comprises an incompressible Newtonian fluid, laminar flow occurs within the film, and only the bearing shell is textured (see Fig. 1). Consequently, the pressure distribution is described by the Reynolds equation as outlined by Stachowiak and Batchelor (2013)

$$\frac{\partial}{\partial s}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial s}\right) + \frac{\partial}{\partial x}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial x}\right) = 6\omega r\frac{\partial h}{\partial s} + 12\frac{\partial h}{\partial t}, \tag{3}$$

where $\mu = \mu(s,x,t)$ is the dynamic viscosity of the oil and $h = h(s,x,t)$ is a gap between the journal and the shell, comprising the combination of nominal gap $h_{\mathrm{nom}} = h_{\mathrm{nom}}(s,t)$, and local deviation $\Delta h = \Delta h(s,t)$ caused by surface texture. It is presumed that all dimples are relatively smooth, meaning there are no abrupt variations in the bearing gap. If both the journal and the shell are circular, nominal gap h_{nom} is defined as

$$h_{\mathrm{nom}} = c_r - e\cos\left(\frac{s}{r} - \phi\right), \tag{4}$$

where c_r is the radial clearance of the bearing, $e = e(t) = \sqrt{y(t)^2 + z(t)^2}$ is the eccentricity and $\phi = \phi(t) = \mathrm{atan2}\left(\frac{z(t)}{y(t)}\right)$ is the attitude angle.

The Reynolds equation is usually solved by the finite difference method, but the finite element and volume methods are also common (Gropper et al., 2012).

3. Pin-on-disc method

To understand the local effects of texture on tribological properties, direct experimental observation of the contact is invaluable. In recent years, researchers have utilized high-speed cameras to observe cavitation phenomena in various surface textures, including a parallel thrust bearing (Cross et al., 2012; Bai et al., 2016), and in a pin-on-disc setup (Hsu et al., 2014). Optical techniques are also suitable for accurately measuring lubricant film thickness. Although these are widely established for lubricant film thickness mapping in point contacts (e.g. Křupka and Hartl, 2007), the number of studies applying these methods to hydrodynamic contacts is very limited (Vladescu et al., 2015).

The pin-on-disc experimental arrangement, involving a small pin interfacing with a rotating disc, is a prevalent technique employed in tribological investigations. Through this approach, crucial tribological parameters such as transmitted forces, oil film height, temperature, etc., can be examined and documented. Initially, it is imperative to establish the experiment's configuration accurately to ensure proper measurement of all essential variables. Subsequently, the creation, solution, and analysis of an appropriate mathematical model constitute the second step.

An experimental approach developed at the Department of Tribology Brno University of Technology, which uses optical methods, was used to study the film thickness, the load-carrying capacity of the contacts, and the influence of the various shapes, locations and geometry of texture (in this case the dimples). The experimental test rig is presented by Hajžman et al. (2023).

The mathematical model used for modeling and simulating measurements on the experimental test rig is based on the Navier-Stokes equation, and the numerical solution using the finite element method is implemented in the COMSOL software. The computational models are refined based on the validation of simulation results with the results of experimental measurements. Typical numerical results in the form of temperature and pressure fields for one of the textured pins are shown in Fig. 2.

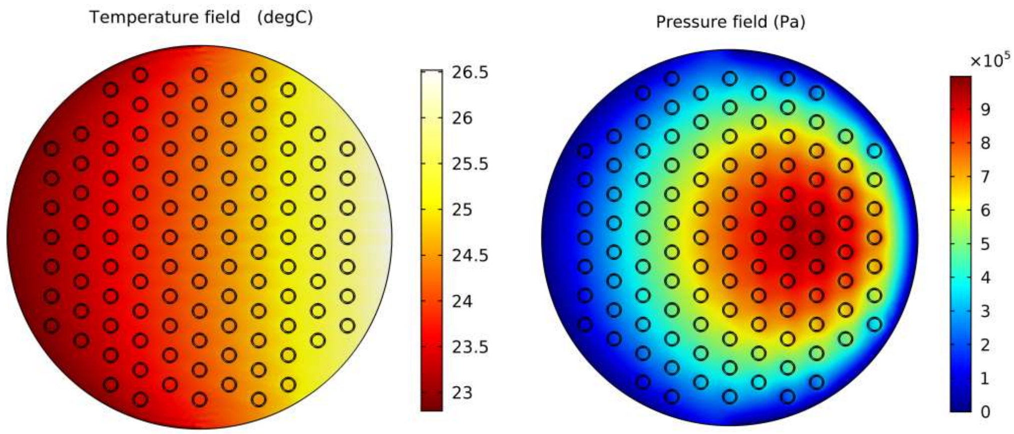

Fig. 2: Example of calculated temperature field (left) and pressure distribution (right) for the full textured pin with dimples.

4. Conclusions

The paper deals with hydrodynamic sliding contact in textured surfaces. Initially, a theoretical framework for modeling textured surfaces of journal bearings is introduced, which is then applied to analyze the dynamic behavior of rotors. Additionally, a pin-on-disc methodology for assessing the characteristics of a lubricated textured surface is presented. By comparing experimental measurements with numerical simulation results obtained from the pin-on-disc method, computational models of lubricated textured pins are refined. The knowledge gained can be used to enhance parameters in computational models of hydrodynamic contact across diverse applications.

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