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Fluid flow across a wavy channel brought in contact

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ABSTRACT

A pressure driven flow in contact interface between elastic solids with wavy surfaces is studied. We consider a strong coupling between the solid and the fluid problems, which is relevant when the fluid pressure is comparable with the contact pressure. An approximate analytical solution is obtained for this coupled problem. A finite-element monolithically coupled framework is used to solve the problem numerically. A good agreement is obtained between the two solutions within the region of the validity of the analytical one. A power-law interface transmissivity decay is observed near the percolation. Finally, we showed that the external pressure needed to seal the channel is an affine function of the inlet pressure and does not depend on the outlet pressure.

1. Introduction

The problem of a thin fluid flow in narrow interfaces between contacting or slightly separated surfaces occurs in different applications. The first example is the sealing problem: seals are used to minimize or prevent leakage of fluids from and into internal chambers of numerous engineering systems, such as gas cylinders, water circuits, lubricated bearings and gears, heat engines and others. Dynamic and static seals are distinguished, the former seal interfaces between surfaces with no relative motion, the latter deal with relatively moving surfaces. Contact and non-contact seals are also distinguished: the former possess contacting parts in the sealing interface, the latter do not.

Hydraulic fracturing is another application which involves interaction of fluid and solid with possible contact between crack faces or/and with a third body, like sand particles [1]. The fluid extraction of shale gas and oil from rocks represents an antipodal problematic to sealing applications, but the physics and fluid-solid coupling remain identical. A slightly different problem involving fluid, solid and contact appears in fatigue-crack growth in lubricated rolling or cyclically sliding contacts [2]. Such an interaction between fluids and solids in contact can be also found in poromechanics [3] and at larger scales in landslides [4], slip in pressurized faults [5], bazal sliding of glaciers [6], and in other applications.

Depending on the application, the fluid can be considered compressible or incompressible (both in gas and liquid states), and it might flow under capillary effect or pressure difference. Fluids in liquid state at high pressure may evaporate due to a pressure decrease along the fluid path or due to temperature increase induced by frictional heating, which results in a mixed gas-liquid-solid problem: a notable example is cavitation in lubrication problems. Compressibility and viscosity of fluid can depend significantly on pressure and temperature within a certain range of loading parameters. Polymers are used in most sealing applications, however, due to fluid-uptake, chemical and thermal degradation, and also the glass transition, their usage is limited; several applications require usage of metal-to-metal contacts in seals. In nature, the problems of interfacial fluids in contact interfaces are relevant for rock materials in terms of hydrogeology, shale gas and oil extraction as well as fracking, and also magma rise in volcanology [7]. In biological systems, the relevant materials are soft tissue and the applications include circulation of blood and other fluids in organisms.

Inevitable roughness, sometimes complemented by on-purpose patterning of engineering and natural surfaces, affects their sealing properties. Inversely, the presence of a fluid in the contact interface may affect the mechanical properties of seals by adding extra load-carrying capacity, changing the interface stiffness and the friction coefficient. For soft materials and high fluid pressures, interface fluids can considerably deform the solids in elasto-hydrodynamic lubrication, however it may be also relevant for static seals [8]. In *contact* seals this nonlinear fluid-solid interaction is intensified by nonlinear contact constraints. This coupling presents the topic of the current study.

The roughness of contacting surfaces [9,10] has strong implications in mechanics and physics of contact: adhesion, friction and wear in dry and lubricated contacts are controlled to a great extent by parameters of the roughness of contacting solids. Mass and energy transport through and across contact interfaces strongly depend on the surface roughness,

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for instance: electric contact resistance, heat conduction between contacting solids and the sealing problem – the topic of the interest of the present paper. The roughness, or more generally the surface geometry, may contain some deterministic features (turned surfaces, patterned surfaces [11]) or be purely random, self-affine [12] down to atomistic scale [13,14]. Surface morphology may be determined by surface processing (polishing, work-hardening), underlying microstructure and its deformation (grain boundaries, plasticity induced roughness [15], persistent slip marks [16], rumpling [17]), corrosion and oxidation; for coatings the roughness is determined by the deposition method (physical vapor deposition, gas dynamic cold spray deposition, electroplating and others), in biology the surface is determined by the tissue growth processes and related instabilities or assigned functionalities [18–20]. The resulting surface morphology may be rather complex and span over many scales from atomistic to structural ones, it can be characterized by numerous parameters, such as standard deviation of heights and height gradient, height distribution, in particular its kurtosis and skewness, power spectral density, spectral moments, etc. For mechanical contact problems, since in most applications only the highest asperities come in contact, an approximation of the roughness by a number of isolated spherical or elliptic asperities results in a rather accurate and helpful model [21–23]. On the other hand, the fluid flow through the free volume[1] is mainly affected by "deeper" surface features: grooves, valleys and dimples.

Numerical analysis of the fluid flow through contact interfaces was carried out between real [24–27] or model rough topographies [28–30]. In contrast to the complexity and lack of scale separation of nominally flat realistic surface roughness, surface patterning allows to use the concept of scale separation to a certain extent and to limit the analysis to major geometrical features of the surface [31–33]. On the other hand, analysis of simple models of surface geometry, for example wavy and bi-wavy models [34–42], helps to understand better local deformation mechanisms in rough contact and the role of patterning for macroscopic behavior. A wavy channel also serves as an important test model in fluid flow analysis [40,43–46]. Here we also consider a periodic wavy channel, but contrary to other flow studies, it is brought in mechanical contact with a rigid flat and the fluid flows across the wavy section in channels delimited by mechanical contact zones. In the first approximation this model represents a "rough" surface with parallel grooves.

To analyze the fluid flow in the contact interface, two problems should be solved: a mechanical problem of the contact between solids with rough surfaces and the problem of the fluid flow through the resulting free volume. If during the loading process the fluid pressure is negligible in comparison to the contact pressure, it is possible to assume that both physics are weakly coupled. This implies that they can be solved separately: firstly, the solid contact problem is solved to obtain the deformed geometry of the channels. This geometry is then passed to the fluid solver, which resolves the fluid flow under the assumption of rigid boundaries. This solution strategy leads to a one-way coupling, whereby the contact problem is independent of the fluid pressure, while the fluid problem depends on the geometry computed by the solid solver. However, it is not rare that in the load interval of interest a stronger coupling between fluid and solid equations is required. For example, it is the case when the local contact pressure is comparable with the hydrostatic fluid pressure. Note that it is always the case near edges of contact zones at which the contact pressure (in the uncoupled case) decreases to zero as $\sim\sqrt{\xi}$, when the distance from the contact edge ξ decreases $\xi \to 0$ [47]. The so-called two-way coupling strategy allows to take into account the fluid pressure distribution and its effect on the deformation of the solid and vice versa: the effect of the elastic deformation on the fluid flow.

In many industrial applications the thickness of the free volume interface between contacting surfaces is quite small, and the flow is often laminar even for gas [8]. Nevertheless, considering turbulent flow could be essential for more demanding applications, like drag delivery, microfluidic chemical reactors, etc. Moreover, we postulate that the variation of the mechanical loading conditions is slow enough compared to characteristic time of the fluid flow, so the flow is assumed to be stationary; capillary actions are neglected, only pressure driven flow is considered. This two-dimensional flow through the contact interface is accurately described by the Reynolds equation [8, 48], e.g.], which is used in this study.

The paper is structured as follows: in Section 2 we formulate the problem to be solved; in Section 3 we recall classical solutions for a wavy profile with a pressurized fluid present in the interface; in Section 4 we obtain an approximate analytical solution; in Section 5 a monolithic numerical scheme which couples the fluid and solid equations is briefly outlined; finally, in Section 6 the numerical results are presented and discussed, and in Section 7 we make conclusions.

2. Problem set-up

We consider an array of wavy channels of length L along OY direction (see Fig. 1(a)) with a sine-shape section

$$z(x') = \Delta[1 - \cos(2x')], \tag{1}$$

where $x' = \pi x/\lambda$, brought in contact with a rigid flat,[2] the pressure driven flow in this channel ($\Delta p_f = p_i - p_o$, where p_i and p_o are the inlet and outlet pressures, respectively) of incompressible viscous fluid is governed by the stationary Reynolds equation for the Poiseuille flow.

We assume an isothermal fluid flow at a temperature at which it does not evaporate under the pressure drop on its way from the inlet to the outlet. The system of equations to be solved takes the following form:

$$\nabla\cdot[g^3\nabla p_f] = 0 \quad \text{in} \quad \Omega_f \tag{2}$$

$$p_f|_{y=0} = p_i, \quad p_f|_{y=L} = p_o, \quad [\nabla p_f\cdot\boldsymbol{e}_x]|_{x=0,\lambda/2} = 0 \tag{3}$$

$$\nabla\cdot\boldsymbol{\sigma} = 0 \quad \text{in} \quad V \tag{4}$$

$$u_x|_{x=0,\lambda} = 0, \quad u_y|_{y=0,L} = 0, \quad \sigma_{zz}|_{z=-\infty} = -p_{\text{ext}} \tag{5}$$

$$g \ge 0, \quad p - p_f \ge 0, \quad (p - p_f)g = 0 \quad \text{in} \quad \partial V, \tag{6}$$

where Eq. (2) is the Reynolds equation for pressure driven stationary incompressible viscous Poisseuille flow, the distance between immobile walls is given by at least C^1-smooth gap distribution $g = g(x, y)$ in the domain Ω_f, which is the closure of the solid volume ∂V projected on the rigid flat, and p_f denotes the fluid pressure. Eq. (3) summarizes boundary conditions for the fluid problem: the fixed inlet p_i and outlet fluid pressure p_o and zero flux at crests of the surface resulting from the problem symmetry. Expression $\nabla p_f\cdot\boldsymbol{e}_x$ is a quantity proportional to the fluid flux in the OX direction (orthogonal to the main flow direction), and $\boldsymbol{e}_x$ is a non-zero in-plane vector collinear with the axis OX. The fluid flux is given by $\boldsymbol{q} = -g^3(\nabla\cdot p_f)/12\mu$, where μ is the dynamic viscosity. Prescribing the fluid flux at the inlet/outlet of the fluid domain would only slightly change the numerical treatment, and since for contact static seals the fluid flow with prescribed hydrostatic inlet and outlet fluid pressures presents a more common situation, for the rest of the paper we will stick to this particular boundary condition. Eq. (4) is the momentum balance equation for the quasi-static solid mechanical problem in absence of volumetric forces, while (5) summarizes boundary conditions for the solid problem, where p_{ext} is the squeezing

[1] By free volume here we mean the separation field between contacting surfaces.

[2] Note that all the discussions are valid not only for an elastic solid with a wavy surface in contact with a rigid flat, but for two elastic solids with the effective wavy roughness given by $z = z_1 - z_2 + c$, where z_1, z_2 determine surface geometries of the two contacting solids, and c is an arbitrary constant. However, for simplicity hereinafter we will assume that an elastic wavy surface is brought in contact against a rigid flat.