Contact of rough surfaces in presence of interfacial fluid flow

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Abstract :

We present recent results on interplay of surface roughness, mechanical contact and interfacial flow of incompressible fluids. First, we present a technique to determine accurately the true contact area in the framework of a spectral boundary element method used to solve the contact between two rough surfaces. This technique enables us to uncover a subtle link between the so-called Nayak parameter and the rate of the contact area growth with the applied squeezing pressure. Apart from studying the growth of the true contact area, we study how the presence of a fluid (compressible and incompressible) in the contact interface affects the contact characteristics. Moreover, an interplay of solid contact and fluid flow as well as an entrapment of the latter are considered. Two different approaches are used to handle this problem. The first one assumes a one-way weak coupling between the solid deformation and the fluid flow. This approach uses the already mentioned spectral-based boundary element method to solve the non-linear contact problem in the context of infinitesimal deformations, a separate finite element solver is used to solve a viscous laminar fluid flow through the opening in the contact interface, which is governed by Reynolds equation. A self-consistent homogenization technique is adapted and used to link the effective transmissivity with the probability distribution of the gap function. A second approach, assumes a strong coupling between fluid and solid equations. Within this approach both equations are solved simultaneously within a monolithic and strongly coupled framework implemented using the finite element method. Some model problems of fluid entrapment and flow through a wavy channel assuming strong coupling of equations are presented. An engineering study of a fluid flow in contact interface between elasto-plastic solids at roughness scale will be also discussed.

Mots clefs : Roughness, Contact, Fluid Flow, Permeability, Fluid Solid Contact Coupling, Trapped Fluid.

1 Introduction

Contact and friction interactions play an essential role in many quotidian contexts, including those related to industry (e.g., tire-road and wheel-rail contacts, electric switches, bearings, and brake systems), everyday human activity (e.g., walking, handling, touching, and sitting) and natural phenomena (e.g., earthquakes, landslides, and glacier motion). Regardless of such prevalence, contact-related mechanisms (friction, adhesion, and wear) are still not fully understood and thus are among the most cutting edge research topics in the mechanical community. It is especially true when the problem under consideration include not only continuum solid mechanics, but also fluid mechanics, thermal and electric fields, chemistry, etc [1].

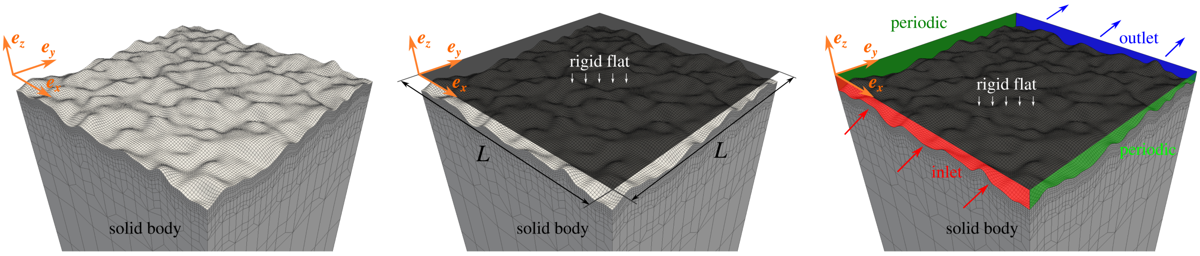
Numerous models of contact-related mechanisms exist at structural scale. They serve to model interfacial normal and tangential stiffness, frictional resistance, material removal on rubbing surfaces (wear), heat transfer between contacting solids, contact electric resistance, adhesion, interfacial fluid flow, microstructural changes in near-contact material layers, fretting life-cycle, debris generation, lubrication, especially in mixed regime, and other mechanisms. Admittedly, all the aforementioned phenomena are strongly related to the surface roughness. The associated models can be incorporated in a macroscopic/structural model via constitutive interfacial equations. These equations can be based either on experimental data, and thus remain purely phenomenological, or can take the microscopic roughness as the starting point. The latter class of models shall have a greater predictive power, and potentially can be used for a large spectrum of applications. However, because of the strong non-linearity of the contact/friction mechanisms and extreme complexity of surface roughness, construction of a reliable analytical micromechanical model presents a serious challenge.

In this work, we make an attempt to summarize recent progress we achieved in understanding of interplay between roughness, mechanical contact and interfacial fluid flow in the simplified context of (i) controlled roughness, (ii) small strain elastic behaviour of material, (iii) absence of relative tangential motion between contacting solids, (iv) isoviscous creeping fluid flow, (v) compressible or incompressible fluid model for trapped fluids. The paper is organized as follows. In Section 2, we briefly present the computational models for solids, fluids and contact as well as methods to solve the related equations. In Section 3, we present recent results on the evolution of the true contact area and the effective fluid-conducting areas. In Section 4, the theoretical results are derived for the permeability of the contact interface. The effect of the trapped fluid is discussed in Section 5. In Section 6, the effect of the strong coupling between solid and fluid equation is briefly discussed.

2 Computational models

Different approaches can be used to solve the problem of permeability of contact interface at microscopic scale. First of all, we would like to mention that too simplified models such as, for example, geometrical overlap of two rough surfaces in which the underlying elastic behaviour of solids is replaced by Winkler's foundation, do not allow to obtain accurate estimation of clearance (or gap) field in the interface, through which the fluid can flow [2]. Therefore, here we will not consider models in which mechanical contact is resolved inaccurately. Before presenting the computational models and schemes, let us assume that we will focus on a simple set-up of normal contact between a rigid flat and a portion of nominally flat rough surface (either with symmetric or periodic boundary conditions prescribed on lateral sides, see Fig. 1).

The simplest method (which can be considered rather accurate for many applications) consists in one-way coupling of solid and fluid equations. The contact problem between two solids with rough surfaces can be solved in absence of fluid, and the resulting gap field $g(x, y)$ can be used to solve Reynolds equation for viscous fluid flow in contact interface [3, 4, 5, 6, 2, 7]. However, if the fluid pressure is high enough, how for example in case of elasto-hydrodynamic lubrication, or for seals used for highly pressurized fluids, a more accurate approach could be needed which takes into account the bilateral coupling of fluid and solid equations [8]. Both one-way and two-way coupling approaches could be implemented using boundary and finite element methods.



(a) (b) (c)

Figure 1 – Set-up : (a) a deformable "rough" solid with periodic or symmetric displacement boundary conditions on lateral sides is brought in contact with a rigid flat (b), and a pressure-driven viscous fluid flows through the contact interface from inlet to outlet with symmetric or periodic fluid-pressure boundary conditions on lateral sides (c).

Note that there is not particular difficulties to use compressible fluid models. The main difficulty, which will be discussed later, is the handling of trapped fluid, interfacial volumes filled with a fluid and surrounded by contact areas. Note that even if for a liquid fluid flow, an incompressible model works rather accurately in a very broad interval of possible loads, an accurate compressibility model of the trapped fluid should be chosen. The initial compressibility (of non-pressurized fluid) of most liquids is smaller than the compressibility of most of solids, however the compressibility of the fluid grows rapidly with the fluid pressure. This effect should be taken into account in the trapped fluid model to enable accurate quantitative and even qualitative results. Finally, it is worth noting that many techniques exist to construct realistic roughness with controllable parameters, for example, filtering white noise with a specially designed low and high frequency cut-offs and appropriate spectral decay [9].

3 Evolution of the contact area and of the fluid-conducting area

The true contact area growth under increasing squeezing pressure $A(p_0)$ controls many aspects of interfacial physics : friction, wear, adhesion and conductivity [10, 11, 12]. Measuring the true contact area is not always a trivial task both in experiments and in numerical simulations [13]. In the latter, the inevitable discretization error can be quite significant, especially when the contact area fraction remains small, which is often the case in practical applications. Therefore, to accurately estimate the contact area, we suggest to use an error-compensation technique, suggested in [14]. Among other things, this technique enabled us to uncover a subtle dependence of the evolution of the true contact area on the Nayak parameter [15, 16]. However, if one is interested in permeability problems, the knowledge of the true contact area A is not sufficient to predict the effective permeability because the remaining area $A_0 - A$ can contain both areas through which fluid can flow A_f but also, out-of-contact areas A_t of trapped fluid, which do not participate in fluid transmissivity. Therefore, the relevant fluid-conducting area is given by

$A_f(p_0) = A_0 - A(p_0) - A_t(p_0)$. We demonstrate that this area grows quite linearly (contrary to the true contact area) with the applied pressure until a certain threshold pressure, at which large areas of fluid becomes trapped which corresponds to pressures near the percolation point.

4 Permeability of contact interface : self-consistent model

Knowing the effective fluid-conducting area is still not enough to predict the permeability of the rough contact interface. Using a self-consistent or effective medium homogenization approach [17, 18], the effective permeability K' can be estimated through the probability density of gap distribution $P(g, p_0)$ in the contact interface for a given squeezing pressure p_0 by solving the following equation :

$$(A_0 - A_f) \int_0^\infty \frac{g^3 P(g, p_0)}{g^3 + K' m_0^{3/2}} \, dg = \frac{A_0}{2}.$$

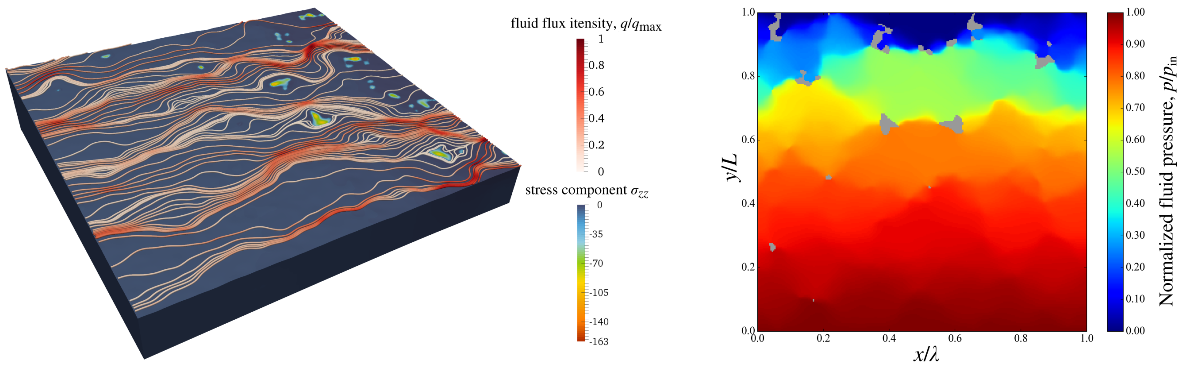
The only difference between this equation and the one found in [18] is that the factor before the integral should contain the total non-conducting area whereas in [18] the authors used the total non-contact area.

5 Effect of the trapped fluid

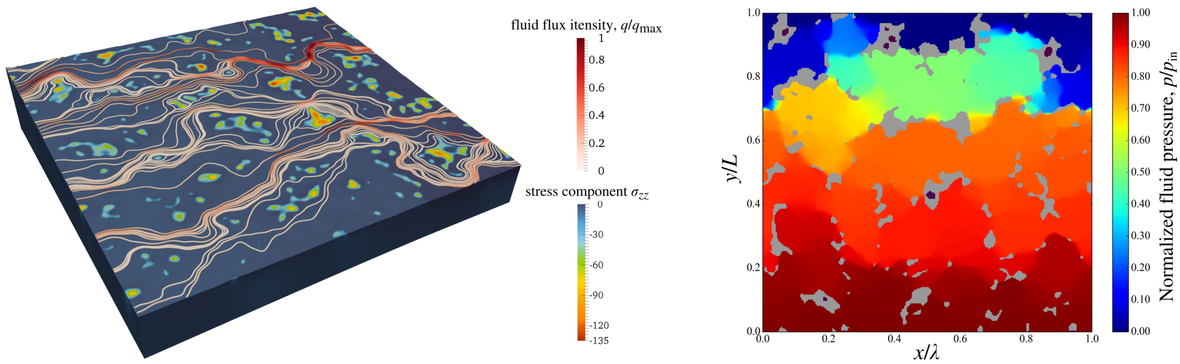
As was already mentioned, the fraction of trapped fluid can be considerable especially near the percolation point. Since the trapped fluid can be pressurized, the external normal load splits between the mechanical contact zones and the areas of trapped fluid, thus reducing the macroscopic frictional resistance of the interface. We recently demonstrated that, apart from this quite evident effect, the trapped fluid can gradually open the trap thus reducing even more the true contact area and the effective frictional resistance [19]. The effect of the trapped fluid is even more peculiar when elasto-plastic material behaviour is considered : an interplay between plasticity, non-linear growth of the contact area and non-linear compressibility of the trapped fluid can result in a strongly non-monotonous evolution of the macroscopic friction coefficient with the squeezing pressure. In a more realistic context, the trapped fluid affects the whole pressure-permeability curve [8].

6 Weak and strong coupling

Finally, we demonstrate how the account for the strong coupling between solid, fluid and contact equations in the computational framework is related to the accuracy of predictions of the model. We compare one-way and two-way couplings on contact topographies of increasing complexity : from (1) simple wavy surface with trapped fluid [19], to (2) a wavy channel brought in contact [20], to (3) a wavy channel with an atoll-type morphology in the trough, and finally to (4) a realistic self-affine roughness [8] (see Fig. 2). We show that a simple shift of results obtained within one-way coupling scheme by a mean fluid pressure can provide us with an accurate enough evolution of permeability with squeezing pressure. However, the related contact area evolution, which is critical for many interfacial effects, cannot be easily predicted without strong two-way coupling. Moreover, the strong two-way coupling allows to link the effective permeability with the squeezing pressure, mean fluid pressure and also to reveal a subtle dependence on the fluid pressure gradient [8].



(a)



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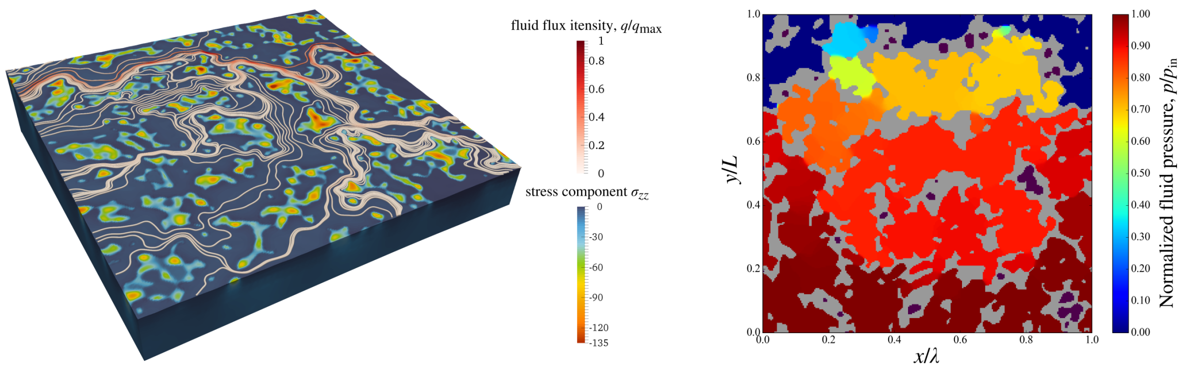

(c)

FIGURE 2 – Example of finite element simulation of a rough contact within a two-way coupling between solid mechanics and fluid flow in the contact interface including the possibility of fluid entrapment. Three instances at different external pressure are shown : on the left the vertical stress component σ_{zz} and current lines (color corresponds to flux) are shown, on the right the corresponding fluid pressure is depicted.

6.1 Conclusion

We derive a consistent computational framework to handle coupling between solid mechanics and fluid in contact interface, which can either flow in the narrow contact interface and/or be trapped and surrounded by contact zones. Numerous aspects of this problem are discussed and illustrated on model and realistic examples. Among computational aspects, several accurate and approximate analytical solutions are derived and compared with numerical results. A novel phenomenological permeability law for rough contact interfaces is derived.

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