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Collective behavior of viscoelastic asperities as a model for static and kinetic friction

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ABSTRACT

We propose a statistical model for static and sliding friction between rough surfaces. Approximating the contact between rough surfaces by the contact of an ensemble of one-dimensional viscoelastic elements with a rough rigid surface, we study the collective behavior of the elements. We find that collective response of the contacts can lead to macroscopic behavior very different from the microscopic behavior. Specifically, various observed features of friction emerge as collective phenomena, without postulating them directly at the microscale. We discuss how parameters in our model can be related to material and surface properties of the contacting surfaces. We compare our results to commonly used rate and state phenomenological models, and propose a new interpretation of the state variable.

1. Introduction

Friction between surfaces plays an important role in phenomena spanning many length scales, and in diverse fields including engineering, biology and geology (Urbakh et al., 2004; Dieterich, 2007). Friction is ubiquitous: it allows us to walk and drive, and it plays a key role in the working of many machines and technologies. At the same time, losses due to friction and wear amount to a significant fraction of the GNP (Peter Jost, 1990; Bhushan, 2013). Thus, the study of friction potentially entails great economic benefits. At small length scales, the ratio of surface area to volume being large, surface forces play a dominant role. Hence, in the design of small scale technologies like MEMS, NEMS and magnetic disk drives, friction has to be given a careful consideration (Tambe and Bhushan, 2004; McFadyen et al., 2006; Bhushan, 2007). Another application of the study of friction is tactile sensing, where the goal is to endow machines with a sense of touch (Scheibert et al., 2009; Wandersman et al., 2011). Various aspects of earthquakes are known to be sensitive to the frictional properties on faults (Scholz, 1998; Marone, 1998; Dieterich, 2007). For these reasons, in the last few decades, there has been a resurgence in interest in friction which, accompanied by the development of new experimental techniques and increased computational power, has resulted in a number of studies of frictional properties of interfaces in different materials at different length and time scales.

The classical picture of friction that emerged from the studies of Leonardo Da Vinci, Guillaime Amontons, and Agustus Coulomb among others is: (a) friction between surfaces is characterized by two numbers, a static friction coefficient μ_s and a kinetic friction coefficient μ_k. μ_s is the ratio between the shear force required to initiate sliding and the normal force, and μ_k is (per unit normal force) the shear force necessary to sustain sliding at a constant (nonzero speed) velocity, (b) the friction coefficients μ_s and μ_k are independent of the normal force applied and the nominal area of the sliding surfaces, and (c) μ_k is independent of the sliding speed (Dowson and Dowson, 1979). Careful experiments on macroscopic systems have shown, however, that μ_s depends on how long surfaces are held in contact before sliding is induced, and μ_k depends on the sliding speed (Rabinowicz, 1965; Dieterich, 1978; Marone, 1998; Christopher, 2002; Beeler et al., 1994). Further, the frictional

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resistance depends not only on the current sliding velocity, but also on the velocity history of the system (Dieterich, 1978; Ruina, 1983; Marone, 1998; Beeler et al., 1994). The independence of the friction coefficients with respect to the normal force and the nominal area of contact has been observed to be a good approximation, except when the normal force varies rapidly (Prakash and Clifton, 1993; Linker and Dieterich, 1992). Section 2 describes some of the experimental results and a class of empirical rate and state laws that has been used to model frictional behavior.

Various theories of contact between surfaces have been proposed. Most surfaces, even those that appear smooth, are rough at the microscale. When two such rough surfaces are pressed against each other, actual contact occurs only at a few spots, at the peaks (asperities) of the surfaces (Fig. 1). There is a large body of literature on single asperity contact, starting from the problem of elastic contact between spheres first addressed by Hertz to theories that include plasticity and adhesion (Bhushan, 1996; Johnson et al., 1971; Derjaguin et al., 1975).

Two broad classes of models have been proposed to connect the asperity scale to the experimentally observed features of the macroscopic frictional behavior. In one class, the contacts are considered to be plastic, following Bowden and Tabor (1986) who suggested that, because of surface roughness, the actual area of contact is only a small fraction of the nominal area, and high local stresses often reach the yield stresses of the materials. They estimated the coefficient of friction as the ratio of shear strength of contacts to the indentation hardness of the material:

$$F_N = A_r \sigma_c, \quad F_S = A_r \tau_c, \quad \mu = F_S/F_N = \tau_c/\sigma_c,$$

where F_N and F_S are the macroscopic normal and shear loads, A_r is the real area of contact, σ_c is the indentation hardness, τ_c is the asperity shear strength, and μ is the friction coefficient. Several subsequent studies have incorporated the time and velocity dependence into that framework by representing the shear force at a contact as the product of the contact shear strength that depends on the sliding velocity and area that depends on the age of the contact (Brechet and Estrin, 1994; Estrin et al., 1996; Berthoud et al., 1999; Baumberger et al., 1999; Putelat et al., 2011). The velocity dependence of the shear strength is attributed to an Arrhenius type activation mechanism while the time dependence of the area results from the creep behavior of the material. The proposed formulations have been able to match various friction observations. In these models, it is assumed that each contact has the same shear and normal force per unit area and the evolution of the contact population is accounted for only by the evolution of the total contact area. As the total contact area changes, the normal force per unit area adjusts, providing the only interaction between the macroscale and the single asperity. Hence this class of models is dominated by the behavior of single asperities and does not include the effects of the statistical properties of the contacting rough surfaces.

In the other class of models, the contacts are considered to be elastic. Since the shear and normal forces are no longer proportional at the microscale for this case, the collective behavior of asperities becomes paramount in explaining the proportionality at the macroscale. Archard (1957) proposed a hierarchical model in which each elastic contact is made of multiple contacts at a smaller scale. This is a precursor to the fractal models of contact (Majumdar and Bhushan, 1991; Persson, 2001; Ciavarella et al., 2000). In the model proposed by Greenwood and Williamson (GW) Greenwood and Williamson (1966), each asperity is assumed to be spherical and a single contact is modeled according to Hertzian theory. This is fitted within a statistical description of the rough surface. These models are capable of explaining the basic observations of proportionality between the shear and normal forces at the macroscale and hence the constant static coefficient. They

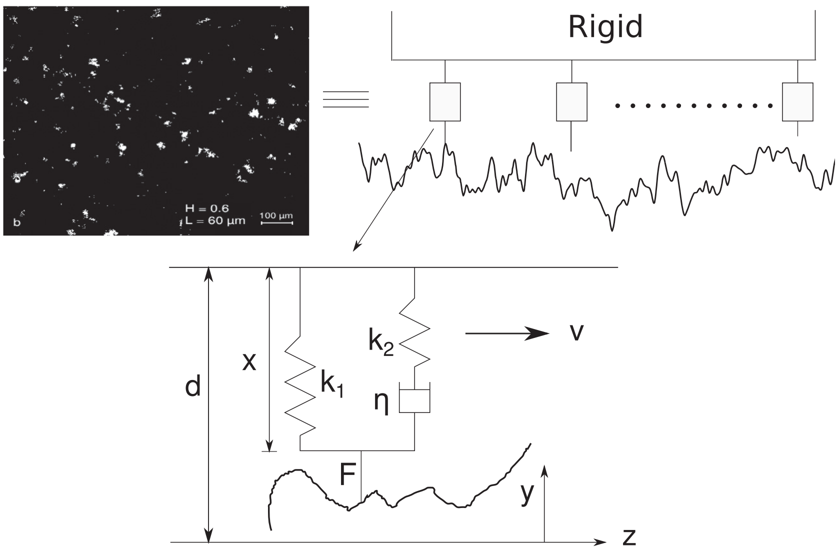

Fig. 1. (Top left) Microscale image of actual contacts (white spots) between two rough surfaces (adapted with permission from Dieterich and Kilgore (1996)). The contacts form at the peaks (asperities) of the surfaces. (Top right) We model the system as an ensemble of one-dimensional elements in contact with a rigid rough surface. (Bottom) Each asperity is represented by a viscoelastic spring-dashpot element.