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Efficient model of evolution of wear in quasi-steady-state sliding contacts

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ABSTRACT

A computationally efficient model of evolution of contact and wear is developed for a general periodic pin-on-flat problem with the focus on the pin-on-disc configuration and Archard wear model. The evolving contact state is assumed to be fully controlled by the wear process except during a short initial transient period controlled by both wear and elasticity. The contact pressure distribution is thus obtained by considering only the local wear model and the geometry of the conforming contact, without referring to the underlying elasticity problem. Evolution of the contact state is then obtained by time integration of the resulting rate-problem, and two computational schemes are developed for that purpose employing either the forward- or the backward-Euler method. The model is successfully verified against a three-dimensional finite element model. A dimensionless wear-mode index specifying the relative magnitude of wear coefficients of the contact pair is introduced, and model predictions are presented as a function of this parameter.

1. Introduction

The wear phenomenon is well known for its high complexity and sensitivity to tribological conditions, and a variety of micro-scale mechanisms inducing macroscopic loss of material at the contact surface have been identified and analyzed. However, general predictive models of wear are still missing, and the simple model of Archard [1] is still the most popular wear model, commonly used in computational practice.

Simulation of progressive wear and associated evolution of contact conditions is also a challenging task. The general methodology amounts to solving a contact problem for a fixed geometry of contacting members and subsequently updating the geometry, all in an incremental manner. Computational approaches employing the finite element method [2–7], the boundary element method [8–10], or specialized contact solvers [11,12] have been developed for that purpose. The geometry is usually updated according to an explicit forward-Euler time integration scheme. This scheme is known to be conditionally stable, and the critical time increment decreases with increasing elastic modulus and with decreasing element size, cf. [2]. A large number of time steps are thus usually needed to avoid instability of the numerical scheme, therefore the overall computational cost is high.

In an attempt to reduce the computational cost, simplified approaches are also developed. For instance, the Winkler model is used to determine the contact pressures in [13], and an elliptical contact area and constant pressure are explicitly assumed in the incremental scheme proposed in [5].

Several approaches have also been developed which consider asymptotic states or steady-state regimes reached in the course of the wear process. A minimization approach is developed in [14] to obtain the worn-out geometry in the asymptotic state under cyclic loading. The formulation includes the elastic response, and it relies on the Green functions for the worn-out half-plane. In [15,16], optimal shapes are determined for steady-state sliding wear processes using the concept of uniform wear over the contact surface. The approach is further developed in [17] for the case of reciprocating contacts. Asymptotic modeling of reciprocating sliding wear is presented in [18,19], and, in the resulting model, it is assumed that the contact pressure is uniform and that the contact area is elliptic.

In this work, a highly efficient model of evolution of contact and wear is developed for a general periodic pin-on-flat wear problem. This class of problems includes, for instance, the popular pin-on-disc and reciprocating pin-on-flat configurations. It is assumed that the evolving contact state is fully controlled by the wear process so that the elastic deflections do not influence the contact pressure and the wear process. Accordingly, the contact pressure distribution is obtained by considering only the local wear model and the geometry of the conforming contact, without referring to the underlying elasticity problem. Evolution of the contact state is then obtained by time integration of the resulting rate-problem, and two computational schemes are developed for that purpose employing either the forward- or the backward-Euler method. In particular, the evolving shape of the contact zone is obtained from the model without any additional assumptions.

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This is a distinctive feature of the present model as compared to other simplified approaches. The model is successfully verified against a full three-dimensional finite-element simulation.

The model considers the general case of both contacting bodies subjected to wear. It is shown that the wear problem formulated in terms of dimensionless quantities depends on a single dimensionless parameter, called the wear-mode index, which specifies the relative magnitude of the wear coefficients of the contact pair.

The paper is organized as follows. In Section 2, the model is introduced, and its special form corresponding to the Archard wear model is derived. Solution schemes, including spatial and temporal discretization, are discussed in Section 3. A study of the predictions of the model is presented in Section 4, including a comparison to the three-dimensional finite element model. In the Appendix, the computer implementation of the model is briefly commented, and the corresponding *Mathematica* code is provided as a supplementary material accompanying this paper.

2. Model of wear-controlled quasi-steady-state sliding contacts

2.1. Assumptions

Wear due to repeated contact and frictional sliding occurs in various tribological pairs. This includes some commonly used tribological test configurations, such as the pin-on-disc, reciprocating pin-on-flat, and pin-on-cylinder tribological tests. Each of these configurations can be classified as a *periodic pin-on-flat wear problem*, cf. Fig. 1. Various pin shapes can also be used in these tests (spherical, cylindrical, conical, etc.). To fix the attention, in this work we shall mostly refer to the spherical pin-on-disc configuration, but the approach is more general and applies to other configurations as well.

Consider contact and wear of two elastic bodies in the periodic pin-on-flat configuration. The contact surfaces are initially non-conforming (point contact); however, as the bodies are worn during the initial period, a *conforming contact* develops in the actual contact zone, i.e., between the wear groove on the disc and the wear scar on the ball, and further evolves during the wear process.

Wear processes are usually slow. Two time scales can thus be introduced [7]: the fast time of the deformation (contact) problem and the slow time related to shape evolution due to wear. Referring to the pin-on-disc test, the fast time corresponds to one revolution of the disc, while the observable wear processes occur at the slow time scale as a result of accumulation of wear over multiple revolutions. Accordingly, the deformation and shape evolution processes can be partially decoupled [7]. In the present context, the deformation problem can thus be treated as a strictly periodic contact problem in which the shape changes due to wear over one cycle are negligible.

The wear problem corresponding to the pin-on-disc (or pin-on-cylinder) configuration can actually be classified as a *quasi-steady-state wear* process, cf. [16,7], meaning that if the shape evolution due to wear was temporarily suppressed then the contact problem would be a steady-state problem (in the frame attached to the ball). In a quasi-steady-state wear process, the contact pressure is thus constant in the fast time scale, though it may evolve in the slow time scale as a result of wear-induced changes of the contact area.

As it is shown in subsequent sections, the shape changes due to wear and the associated evolution of contact pressures can be determined by considering only the wear model and the kinematics of the progressive wear process. Elastic deformations are thus not considered, and the usual contact problem is not solved. This requires an additional assumption that the elastic deflections are small compared to the shape changes due to wear. This is a typical situation, for instance, in the case of metallic or ceramic contacts. In this sense, the contacting bodies are treated as rigid, and the model will be referred to as *the rigid-wear model*.

The present model considers the general case when both contacting bodies wear away, i.e., both the wear scar on the pin and the wear groove on the disc form and evolve during the wear process. The situation when the disc does not wear away is a trivial special case. At the same time, the present model is not directly applicable in the other limiting case when the pin does not wear away: the shape of the wear groove is then trivially predicted (assuming the elastic deflections are negligible), but neither the contact pressures nor the contact zone can be determined without solving the complete contact and wear problem.

Two additional technical assumptions are also adopted in the present model. It is assumed that the normal to the pin surface is not affected by the wear process (i.e., the slope of the wear groove is assumed small), and the disc is assumed to be homogeneous along the sliding direction.

2.2. Geometry of the conforming contact zone

Consider a contact and wear problem in the pin-on-disc configuration, where both the pin and the disc are subjected to

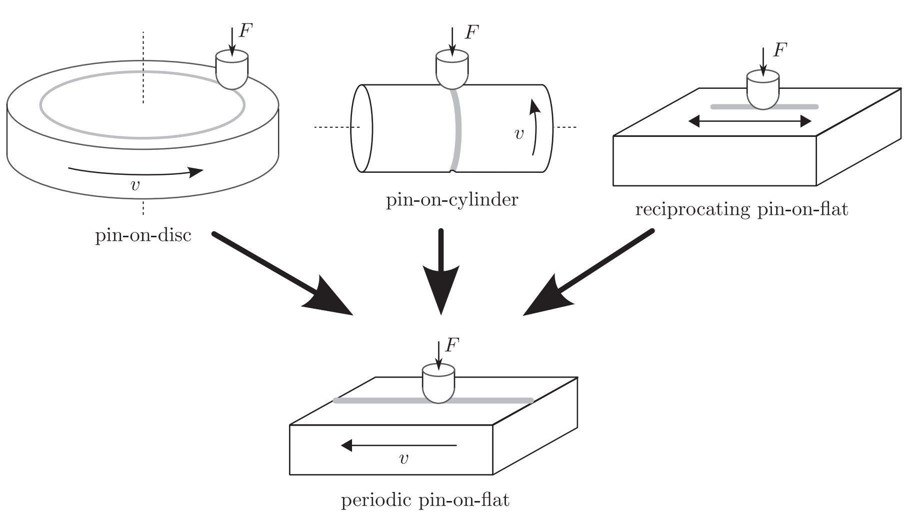

Fig. 1. Three commonly used tribological tests and their simplified representation.