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Numerical multiscale modelling and experimental validation of low speed rubber friction on rough road surfaces including hysteretic and adhesive effects

Paul Wagner[a,*], Peter Wriggers[a], Lennart Veltmaat[a], Heiko Clasen[b], Corinna Prange[b], Burkhard Wies[b]

[a] Institute of Continuum Mechanics, Gottfried Wilhelm Leibniz Universität Hannover, Appelstraße 11, 30167, Hannover, Germany
[b] Continental Reifen Deutschland GmbH, Jädekamp 30, 30419, Hannover, Germany

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ABSTRACT

A multiscale finite element framework for the calculation of sliding rubber samples on rough surfaces is proposed. The two essential physical contributions hysteresis and adhesion are modelled. Hysteresis originating from the viscoelastic nature of rubber materials is included directly by incorporating the rough surface in the calculation with microscopic details and without transformations or a reconstruction of the surface. The adhesive interaction is introduced by a macroscopic shear stress law coupled to the hysteresis simulation by the evaluation of the relative contact area. The assumed mechanisms and the framework are explained in detail and are used to validate the method for experimental results of different materials for low sliding speeds.

1. Introduction

1.1. Motivation and goals

The contact of car tires with road tracks is a research field of high practical importance since grip properties during tire-road interaction have a direct impact on safety issues. In order to improve tire properties, a deep understanding of the tire-road contact mechanics and the underlying rubber friction physics are essential. The major goal of our work is to predict performances of different rubber materials on rough road tracks. Besides, our numerical studies provide access to data that is not reachable in experiments like local pressures, dissipated energies, or contact area. As a result, our method can give additional insight into the physics of rubber friction.

1.2. Background of rubber friction

The frictional response of sliding rubber is determined by the rubber material properties, the rough counter surface including its condition (dry or wet for example), and the global test parameters (normal load, velocity, temperature). These statements are based on a lot of experimental studies starting with early works revealing pressure-dependence (cf. [1]). In [2], non-linear velocity- and temperature-dependence of rubber friction is reported. Further experiments performed with modern test rigs for high velocities and temperature measurements can be found in [3–6].

Experimental and analytical studies also link the measured responses to physical effects. They provide theories and statements about the shares of each effect on the overall frictional response. In [7,8], the velocity-dependence of the frictional response is linked and correlated to the viscoelastic material properties of elastomers providing a first theory for hysteretic friction.

In contrast to hysteretic friction as a volumetric effect, adhesive friction is a surface effect induced by intermolecular effects. For an overview of adhesive interactions see [9]. Details of both effects are explained in Section 2.

These two effects (hysteresis and adhesion) can be considered as the main effects contributing to the overall friction force. Additionally lubrication, cohesion and interlocking are often observed in experiments. Viscous forces (lubrication), wear- (cohesion) and temperature-effects play a major role for large sliding velocities, which are out of scope of the present work. Furthermore the validation is carried out for low macroscopic velocities where these effects are assumed to be negligible and a large contribution of adhesion is expected (cf. [10,11]).

1.3. Modelling of rubber friction

In [12–14], analytical approaches dealing with hysteretic friction

* Corresponding author.
E-mail address: wagner@ikm.uni-hannover.de (P. Wagner).

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are proposed. These works are based on an analysis of the dissipated energy induced by the rough surface revealing the possibility to study elastomer friction for a wide parameter range. Due to the fractal nature of the rough surface (cf. [15]), a power spectral density (PSD) or a height difference correlation (HDC) can be used to represent the surface. Furthermore, different analytical contact theories are introduced in [13,14], see also [16] for an overview. The approach introduced in [14] is enhanced by an adhesive contribution in [17] adding an adhesive coefficient of friction to the hysteretic response based on the contact area and an interfacial shear stress representing a free parameter. In [18] a theory is provided that states a bell-shaped character of the shear stress over increasing velocity. Following the introduced assumptions and theories for adhesion in [10,11,19] different velocity-dependent laws for the shear stress are introduced, fitted to experiments and compared for different global conditions. Especially, in [11] the proposed law for the shear stress (see Section 4) is linked to the assumption of rubber chains undergoing bonding-stretching-debonding cycles with the rough surface (details are provided in Section 2). Furthermore, for example in [17] assumptions for the share of hysteresis and adhesion for different surface conditions are provided proposing that adhesion is activated on dry surfaces and suppressed on rough surfaces covered with a water-detergent film, see Section 2 for further details. Different rubber materials in the small velocity range are studied in [11] providing good agreement of the theory with respect to friction measurements enhanced by an expansion of the law for different temperatures by the use of an Arrhenius-like shift factor. The proposed adhesion law is used in this work without the expansion to different temperatures in order to validate small velocity measurements at room temperature T=20 °C, see Section 6.

Due to the presence of many different length scales in real rough surfaces, multiscale approaches are especially suited to tackle these kinds of contact problems. Numerical multiscale approaches for rubber friction using finite element models are developed in [20–22]. The common feature of all cited multiscale frameworks is a decomposition of a complex contact problem into separate length scales and the use of homogenization techniques. A coupling between two scales is established through passing contact values (pressure, velocity) of the larger scale (macroscopic scale) to the smaller scale (microscopic scale). A microscopic coefficient of friction originating from the microscopic details of the surface is gained by homogenization and passed back to the macroscopic scale. Contact homogenization approaches can be used if the scales are separated meaning that the characteristic macroscopic length scale is a few times bigger than the microscopic length scale. In [20] the complex dynamic contact interaction of a rubber block with microscopic moving particles is studied accomplished by homogenization studies varying rubber block dimensions and further parameters. The contact homogenization technique is transferred for the first time in [21] to the contact of a rubber block with stationary rough road surfaces. Nevertheless, the rough surface is decomposed by a certain number of sinusoidal functions approximating the HDC function of the real rough surface. The treatment of the rough surface reveals problematic properties with respect to converging global results, because a small change in the used sinusoidal functions leads to large changes in the gained macroscopic coefficient of friction. Therefore, in [22] a different treatment of the rough surface is proposed reconstructing the surface with a PSD-transformation including more frequencies and amplitudes in the analysis. As a next step in this work, the rough surface is directly included in the numerical setups without idealizations like in [21].

A lot of microscopic aspects are investigated in several works studying parameters that influence the outcome of the homogenization procedure. For example in [23] the difference between displacement and traction driven boundaries is investigated. Among other aspects for homogenization on sinusoidal profiles, in [24] the compression time is identified as an influencing parameter that needs to be adopted to avoid large oscillations of the resulting coefficient of friction. In [25] complex geometries of micro particles are introduced followed by the introduction of rough surface profiles in [26,27] providing the basis for the later proposed multiscale method with direct inclusion of rough surface profiles. In addition, in [28] a comparison between an analytical and a numerical calculation on sinusoidal functions with different parameters is executed revealing the benefit of numerical approaches by introducing geometrical and material non-linearity.

A complex thermo-mechanical numerical multiscale setup for rough surface contact problems based on homogenization is introduced in [29]. Furthermore, this framework is extended to isogeometric analysis in [30] and to dissipative interactions in [31]. Numerical investigations dealing with the determination of the thermal contact conductivity are explored in [32,33]. Additionally, in [34–36] the previously mentioned analytical approaches are extended to thermal interactions between rubber and rough surfaces. The cited studies dealing with thermal interactions would provide a basis for an extension of the proposed multiscale framework to larger velocities with non-negligible temperature effects.

The proposed numerical multiscale framework in this work is based on the publications [20–22]. A separation of rough surface length scales and time homogenization in a two-dimensional plane strain setup is applied. Some changed and adapted features are described in detail in Section 3. A macroscopic adhesion law adapted from [10,11] is implemented in the finite element multiscale setup and compared to experiments. Direct numerical modelling of adhesion with complex interface kinematics is for example investigated in [37,38], an overview of numerical approaches for adhesion can be found in [39].

1.4. Outline

First, hysteretic friction including the possibilities for an implementation within a finite element framework, the adhesion mechanism, and the shares of each effect on the final friction response are explained in Section 2. The multiscale methodology for hysteretic friction is outlined in Section 3. The used assumptions for adhesion and the inclusion of an adhesion law into the multiscale setup are described in Section 4. A mechanical study of hysteretic friction on the microscopic scale is evaluated in Section 5, providing important information for the following validation. The validation of the numerical approach with experiments is performed in Section 6 using three different rubber materials for low sliding speeds. Finally, concluding remarks are given in Section 7.

2. Rubber friction mechanisms and modelling aspects

In this section a background for the modelled contributions, hysteretic and adhesive friction, is provided in detail. Assumptions and important aspects for the solution of the problem with finite elements are given.

2.1. Modelling hysteretic friction

Viscoelastic materials show the effect of energy dissipation inside the material during cyclic loading and unloading. Furthermore, the amount of dissipated energy depends on the applied frequency of the cyclic loading and the used rubber material.

In the case of a sliding rubber block on a rough surface, asperities induce hysteresis inside the rubber material. The material response leads to a horizontal resistance force, called hysteretic friction, see Fig. 1(a). A global velocity change induces the excitation of different frequencies. Therefore, a velocity-dependence of the global frictional response is observed in experiments, compare Section 1.2. Additionally, [12,13] point out that microscopic surface asperities are responsible for high local strains in the rubber and contribute significantly to the global response. Thus, the microscopic structure