

A Multiscale Model of a Disc Brake Including Material and Surface Heterogeneities

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ABSTRACT

During friction it is well known that the real contact area is much lower to the theoretical one and that it evolves constantly during braking. It influences drastically the system's performance. Conversely the system behavior modifies the loading conditions and consequently the contact surface area. This interaction between scales is well-known for the problematic of vibrations induced by friction but also for the thermomechanical behavior. Indeed, it is necessary to develop models combining a fine description of the contact interface and a model of the whole brake system. This is the aim of the present work.

A multiscale strategy is proposed to integrate the microscopic behavior of the interface in a macroscopic numerical model. Semi-analytical resolution is done on patches at the contact scale while FEM solution with contact parameters embedded the solution at the microscale is used. Asperities and plateaus are considered at the contact interface. FFT techniques are used to accelerate the resolution at the micro-scale. As an example the multiscale model is applied into a complex value analysis used to identify modal coupling in NVH simulations. With this model the interaction between non uniform surface and system dynamic behavior is clearly shown. The contact surface variations clearly affect the modal coupling and therefore noise propensity.

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INTRODUCTION

Braking performance simulation is a huge challenge as it needs to consider coupling between several physics (mechanics, thermic, tribology...) and between several scales. It is now well known that there is a strong interaction between phenomena at the contact interface and the system behavior. For example recent works about friction-induced vibration for braking applications have shown that the contact distribution plays a key role in the determination of unstable frequencies leading to squeal [8,12,16]. On the numerical point of view, considering microscale at the contact and macroscale of systems with many components is a complex challenge especially for braking analysis as the problem varies during the application. Usually only one scale is considered, the other one is simplified, for

example in [7] with a fine roughness model but a discrete model of the system or in [8] with an FEM model of the system but limited refinement at the interface. It is then necessary to imagine efficient methods of multiscale analysis. This is the aim of the present work.

Considering the problem of contact simulation at the microscale between rough surfaces, there were many developments in numerical simulations of contact between rough surfaces in the last few years. Two main techniques can be distinguished: the finite element method and the half-space solution. In the first class of methods, the problem is solved using optimization methods [20] and the computational time is high since surface discretization must be enough fine to capture all roughness details. Using this method, elastic contact and inelastic plastic contact have been analyzed [9,13], the results obtained are

quite similar to analytic predictions. Finite element method (FEM) was also used in many works to define some micro mechanical contact laws that are embedded in macroscopic models. In those approaches a RVE (Representative Volume Element) is defined and many calculations are made to get a macroscopic physical quantity that depends on roughness. For example in [22], a phenomenological contact model based on finite element calculations has been proposed to rapidly analyze the plastic contact of a rough surface. Similarly in [4,21] a multi-scale approach has been developed to obtain a homogenized coefficient of friction that reflects the roughness's influence on a frictional contact. Comparing to FEM methods, the second class of numerical methods is more attractive because of its reduced computational time. In those methods, only the surface is discretized and the solid is considered as a half space. The resolution is done using Boussinesq solution [10] for elastic half spaces. This technique has been used in many works [2,15,19,23] and provide more accurate results. Using the FFT technique, a fast version of this method has been developed in [11] to model the contact of heterogeneous half spaces, and in [6] to model the fretting problems.

In the present work, our interest is focused in friction brakes where contact status evolve continuously, and the size and distribution of contact zones influence drastically the global behavior of the surrounding components [5,12]. The main purpose is to propose a numerical strategy that allows to consider contact roughness in a large-scale model. As mentioned before, the explicit meshing of contact roughness in this kind of models is computationally expensive, so it is needed to define a multi-scale homogenization strategy allowing to consider roughness effects. Moreover this multiscale homogenization technique must be done zone by zone, so that each zone has its local contact properties. Hence the implementation of such technique allows to get a kind of macroscopic contact localizations depending only on the size and the geometry of each homogenized zone. Thus, the strategy incorporates two main steps. The first one is to analyze the micro-mechanical behavior of an interface involving rough surfaces. The second one aims to integrate this behavior in a macroscopic numerical model. The potential theory is used to describe surface displacements under contact stresses at the micro-scale. The body is considered as an elastic homogeneous half space. Asperities and plateaus on the contact surface are both considered, in the way of considering wear effects. At the macro-scale a perfect interface is considered, enriched by contact model taking into account the microscopic mechanical behavior.

The multiscale strategy is first described followed by the integration in a braking simulation and an application of the influence of roughness in NVH simulations.

MULTISCALE MODELING OF CONTACT INTERFACE

Global Strategy

Considering a rigid plan making contact with an elastic body represented by a cube in [fig.1](#). Let us take a zone from the contact interface. By zooming on this zone, the real surface is rough. The aim of this work is to integrate the microscopic interface behavior in the large scale numerical model. Since roughness scale is much smaller

than the structure ones, modeling strategy considers a perfect interface at the macro scale, enriched by contact model taking into account the microscopic asperities (see [fig.2 \(a\)](#))

For that purpose, the strategy builds on the penalty method. This technique pairs up contact pressure p_n to the interface gap g_n by contact stiffness K_n , such as : $p_n = K_n(g_n) \cdot g_n$. The objective here is to identify the contact law by choosing properly the stiffness parameter. It is made depending on surface roughness.

Practically, contact surface is divided into many zones, where each zone has its proper geometry and roughness. For each zone, stiffness is computed using a micro-contact model that considers material properties and roughness. Indeed, on the one hand, by choosing a convenient micro model, the contact pressure p_n can be expressed in terms of real displacement δ_r . On the other hand, the elastic displacement δ_p can be calculated, corresponding to perfect contact situation (see [fig.2 \(b\)](#)). Thus, from the two situations, the gap can be computed by $g_n = \delta_r - \delta_p$, and from this equation, the stiffness can be deduced by a simple inversion and derivation operations.

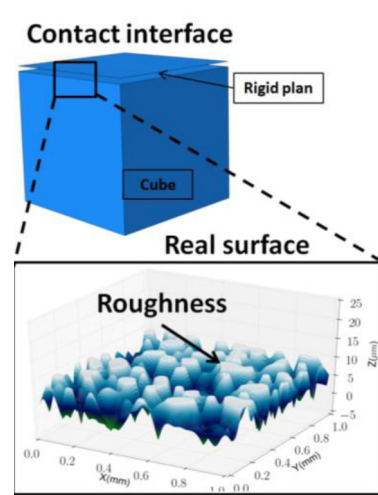


Figure 1. Scheme of multi-scale model with a real contact interface

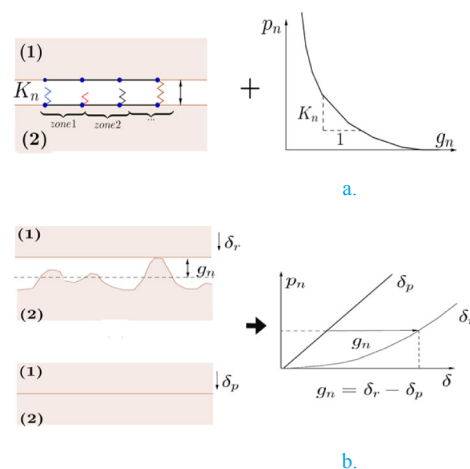


Figure 2. Scheme of the proposed strategy of contact enrichment

Using this technique, the microscopic behavior of an interface is easily integrated in a large scale numerical model and a macroscopic accurate description of the interface is achieved in a relatively small computational time. In the following, a micro-contact model is proposed to analyze the real interface evolution.

Micro-Contact Model

Surface roughness can be seen as a random set of parabolic asperities. When contact occurs, surface asperities deform elastically and a circular contact zones appear above them (see [fig.5](#)).

Now if the plan is sliding, shear stresses lead to an expansion of contact zones. Additionally, due to wear effect, a part of the debris from the interface is tracked into the contact and compacted. It forms smooth and flat contact zones, namely called "contact plateaus" which have "arbitrary" shapes. These zones are discretized into many square patches (see [fig.3](#)). The contact is mainly concentrated on these zones and the asperities.

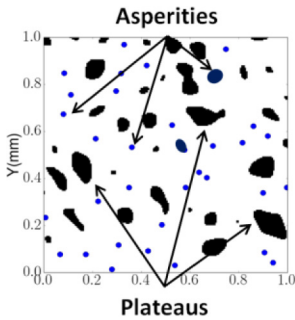


Figure 3. Surface asperities and plateaus

In order to solve the elastic problem combining the presence of plateaus and the asperities, one can express the complementary potential energy given by [10]

$$U_E = \frac{1}{2} \int_{\Gamma_c} p u_z dS - \int_{\Gamma_c} p \delta dS$$

where Γ_c is the contact zone, u_z is the displacement field and p is the pressure field and δ is the prescribed displacement field.

N_p patches and N_a asperities are assumed to be potentially in contact. If the body is considered as an elastic homogeneous half space, potential theory ([3], [10], [18]) is used to describe surface displacements under contact stresses, and this energy can be expressed in a discretized form as:

$$U_E = \frac{1}{2} \sum_i^{N_p} p_i A_i \left(\sum_k^{N_p} p_k L_{ki} + \sum_j^{N_a} G_{ji} \right) + \frac{2 E^*}{3} \sum_j^{N_a} \frac{a_j^3}{R_j} \left(\sum_k^{N_p} p_k L_{kj} + \sum_{l \neq j}^{N_a} G_{lj} + \frac{4 a_j^2}{5 R_j} \right) - \sum_i^{N_p} p_i A_i \delta_i - \frac{4 E^*}{3} \sum_j^{N_a} \frac{a_j^3}{R_j} \left(\delta_j - \frac{1}{5} \frac{a_j^2}{R_j} \right)$$

where

$$G_{ik} = \begin{cases} \frac{a_i^2}{2 R_i} \left(2 - \frac{d_{ik}^2}{a_i^2} \right) & \text{if } d_{ik} \leq a_i \\ \frac{a_i^2}{\pi R_i} \left[\left(2 - \frac{d_{ik}^2}{a_i^2} \right) \arcsin \left(\frac{a_i}{d_{ik}} \right) + \sqrt{\frac{d_{ik}^2}{a_i^2} - 1} \right] & \text{else} \end{cases}$$

and

$$L_{ik} = F(x_{ik}, y_{ik}) + F(y_{ik}, x_{ik}) - F(-x_{ik}, y_{ik}) - F(-y_{ik}, x_{ik})$$

with

$$F(x, y) = (x + l_i) \ln \left(\frac{y + l_i + \sqrt{(y + l_i)^2 + (x + l_i)^2}}{y - l_i + \sqrt{(y - l_i)^2 + (x + l_i)^2}} \right)$$

l_i is the patch half width, p_i is the pressure, A_i is the patch area, δ_i is the prescribed displacement, a_j is the asperity contact radius, R_j is the asperity radii of curvature, (x_{ik}, y_{ik}) are the relative coordinates of the k^{th} element in the basis located at the i^{th} element and d_{ik} is the corresponding distance. Note that these analytical expressions are obtained from Love solution and Hertz theory [10] for, respectively, plateaus and asperities. They are derived from potential theory applied to the elastic deformation of solids.

Solving the contact problem is to minimize U_E subject to $p_i \geq 0$ and $a_j \geq 0$. The FFT technique can also be used to accelerate the solving scheme, especially if there is a big number of plateaus. Once these variables are determined, the total load is expressed by

$$P = \sum_i^{N_p} p_i A_i + \frac{4 E^*}{3} \sum_j^{N_a} \frac{a_j^3}{R_j}$$

The couple P and δ gives a full description of the microscopic interface behavior considering both asperities and plateaus. It is used to embed the large scale numerical model as explained before. In [fig.4](#) and [fig.5](#), an example of the distribution of vertical displacement and contact pressure is presented. These computed fields correspond to the surface presented in [fig.3](#) and a displacement of $\delta = 2.5 \mu m$. Note that this methodology has been validated by comparing results with FEM calculations done with very fine mesh of roughness discretization [18].

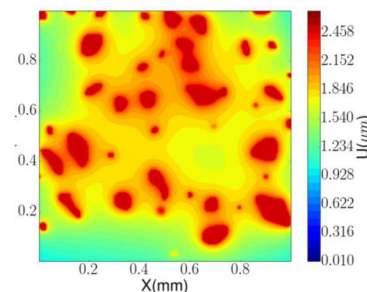


Figure 4. Vertical displacement field with the surface of [fig.3](#)