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A contact mechanics study of 3D frictional conformal contact

Julio Blanco-Lorenzo, Javier Santamaria *, Ernesto G. Vadillo, Nekane Correa

Department of Mechanical Engineering, University of the Basque Country UPV/EHU, Plaza Ingeniero Torres Quevedo 1, 48013 Bilbao, Spain

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ABSTRACT

A contact mechanics study of three-dimensional conformal contact with friction is presented, based on numerical calculations with Finite Element models and an extension of Kalker's exact contact theory which takes into account the effects of conformity. Both the normal and the tangential parts of the contact problem are studied in situations with different conformity levels, up to total contact angle variations in the contact patch of about 100°, assessing the particular characteristics brought about by conformity and the differences with respect to non-conformal contact. The study may be of interest in important industrial applications where conformal contact may be found, such as rolling bearings or the wheel-rail case.

1. Introduction

It is essential to use adequate contact models in vehicle dynamic MBS simulations. Precise contact modelling is even more imperative for the study of tribological phenomena in the contact interface such as wear and rolling contact fatigue. Notably in the wheel-rail case, the hypothesis of non-conformity is adopted as a simplifying assumption in most wheel-rail rolling contact theories. However, in some situations the contact area may become considerably curved in the lateral direction, thereby compromising the adequacy of a non-conformal analysis. Moreover, conformal rolling contact is also common in other industrial application as important as rolling bearings.

2D conformal cylindrical contact is characteristic of pinned joints, which are present in numerous engineering applications, and has been extensively studied in the literature. Following the work of Persson [1], in Ref. [2] the formulation of the 2D conformal cylindrical contact without friction was developed, obtaining the load-contact angle variation relationship in closed form, and extending the range of validity of the formulation to any value of Dundurs' first material parameter. In Ref. [3] the study was extended for the case of non-zero Dundurs' second material parameter, solving numerically the governing integral equations of the problem. Further, an analytical approximation was proposed for the load-contact angle variation relationship, based on the assumption, verified by the numerical calculations in the work, that the impact of Dundurs' second material parameter on the pressure distribution (for a given contact angle variation) can be neglected. The analytical load-contact angle variation relationship was also derived in Ref. [4] for the case of identical materials in contact, and a fracture mechanics study was conducted considering a radial crack emanating from the surface of the circular hole of the plate. In Refs. [5,6] the formulation for the 2D conformal cylindrical contact problem with friction was developed, for the case of rigid and elastic pin respectively. The influence of remote stresses in the plate was incorporated in the analysis. The analytical Green's functions of the displacements of the pin and the hole subject to boundary point loadings were used, and a numerical method was proposed to solve the governing singular integral equations of the problem, valid provided the contact is not split in more than one contact patch. Double conforming cylindrical contacts without friction, in which an intermediate annular elastic body between the pin and the infinite elastic plate with a hole was present, were studied in Refs. [7,8]. The displacements of the pin and the plate were calculated making use of their corresponding Green's functions, and those of the ring were calculated by means of a Fourier series technique. In Ref. [8] the model was extended to cope with interference in the contact, and the influence of geometric irregularities on the resulting contact pressure distributions was studied. Other references of studies about 2D conformal contact may be found in Ref. [9] for instance.

The works about 3D conformal contact in the literature are comparatively few compared with 2D contact. Refs. [10,11] are early examples of wheel-rail conformal frictionless contact studies. The study of frictional contact entails more complexity, and has been less studied than frictionless contact. In Ref. [12] an analysis method for conformal contact problems including friction in the interface was proposed. The normal part of the contact problem was solved with a simplified procedure assuming an elastic behaviour of the solids in contact similar to the elastic half-space, and the tangential part of the contact problem was

* Corresponding author.
E-mail address: javier.santamaria@ehu.eus (J. Santamaria).

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solved with FASTSIM [13,14], but accounting for the non-flat geometry in the calculation of the rigid slip velocities. A simplified method based on the strip theory was used in Chapter 8.5 of [15] to study frictional conformal rolling contact. STRIPES [16,17] is another simplified frictional rolling contact algorithm, which is based on the idea of dividing the contact patch in longitudinal strips, and is able to deal with contact cases with conformal geometries. In Ref. [18] Kalker's exact rolling contact theory [13,14] was generalized for conformal contact by replacing the half-space influence coefficients (ICs) by appropriate ICs for non-planar geometries, and was later used in Ref. [19] for a case study with conformal contact. The same approach was applied in Ref. [20] with Kalker's exact contact theory programmed in the CONTACT software [21].

Recently, the authors have investigated about the three-dimensional wheel-rail conformal rolling contact [22,23], considering cases with moderate total contact angle variations in the contact area, of up to about 41° in the lateral direction. In the present work the study on three-dimensional conformal contact with friction is further extended to higher levels of conformity. For this purpose, both FE models and an extension of the exact contact theory for conformal contact, previously described by the authors in Ref. [23] and which will be referred to as CECT (Conformal Exact Contact Theory) here, are used. The qualitative differences between conformal and non-conformal contact are pointed out, and the adequacy of currently widely used non-conformal contact models under different conformal contact situations is discussed. In this way, the paper provides insight into some phenomena related to 3D conformal contact, and examines the errors which may arise when disregarding the effects of conformity in the analysis. The work may be of particular interest in applications in which accurate contact mechanics results are necessary in conformal contact conditions, such as in analyses of damage phenomena in the contact interface like wear.

2. Description of the models

In this section the most relevant aspects of the models used in this work are summarized. On the one hand, Finite Element models, and on the other hand, an extension of Kalker's exact rolling contact theory for conformal contact, developed along the same lines as in Refs. [18] and [20] and designated here as CECT, are used. A more detailed description of the models may be found in Ref. [23].

Before going further, a brief description of the representation of the conformal contact geometry is given. The three-dimensional contact between a body of revolution and a body with constant cross section in the longitudinal direction is considered, which will be called the wheel and the rail respectively. The contact is assumed to be conformal in the plane perpendicular to the rolling direction only, as represented in Fig. 1, and non-conformal in the longitudinal or rolling direction. As the contact angle is variable in the lateral direction, in order to provide a quick measure of it in each studied case, the concept of the mean contact angle is used. This is defined as the contact angle at the first or rigid point of contact (which will usually be at or near the central point of the contact patch). The local quantities of interest in the contact (stresses, deformations, etc.) are expressed in the local contact coordinate system. This is a Cartesian coordinate system tangent to each point in the contact, its three principal orthogonal directions being defined as the longitudinal (rolling) x, the tangential lateral s, and the normal n axes. The origin of the x and s coordinates is taken to be at the first or rigid point of contact.

2.1. Finite Element models

The Finite Element Method offers the possibility to model diverse physical phenomena, considering dynamic effects, complex material behaviours or contact interactions for example. However, its application to rolling contact mechanics poses some challenges, coming basically from the fact that the region to be modelled has to be typically much larger than the (contact) region of interest. The resulting models frequently have hundreds of thousands of degrees of freedom, and have high computational costs. Additionally, usually a fine-tuning process of the model and associated parameters such as numerical tolerances or incrementation controls becomes necessary in order to obtain valid results for a given application, see Ref. [24] for example.

In this work detailed 3D Finite Element models are constructed meshing a part of both solids in contact with linear solid elements, with a high refinement around the contact area so that the contact patch is discretized in up to around 40 elements in each direction. With these models, static contact, transient or steady rolling contact cases can be simulated. The contact simulations are performed imposing predefined motions to the central point of the wheel in successive steps. For the steady state rolling contact simulations (Section 3.3) the results are obtained after a rolling length of about 3 times the total longitudinal

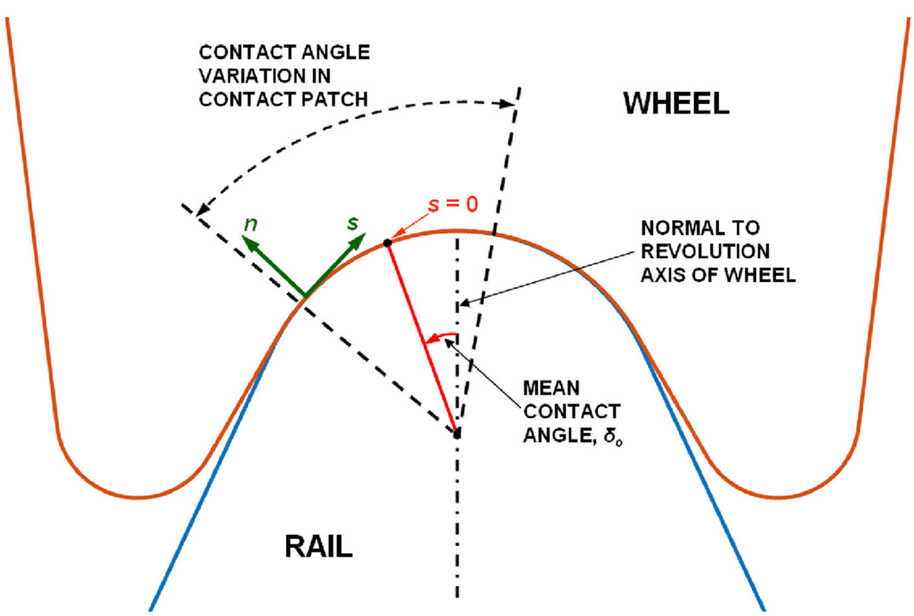

Fig. 1. Conformal contact geometry with definition of mean contact angle δ_o and local contact coordinate system with directions s and n. Section view, perpendicular to the rolling direction x.