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# Importance of tread inertia and damping on the tyre/road contact stiffness

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ABSTRACT

Predicting tyre/road interaction processes like roughness excitation, stick-slip, stick-snap, wear and traction requires detailed information about the road surface, the tyre dynamics and the local deformation of the tread at the interface. Aspects of inertia and damping when the tread is locally deformed are often neglected in many existing tyre/road interaction models. The objective of this paper is to study how the dynamic features of the tread affect contact forces and contact stiffness during local deformation. This is done by simulating the detailed contact between an elastic layer and a rough road surface using a previously developed numerical time domain contact model. Road roughness on length scales smaller than the discretisation scale is included by the addition of nonlinear contact springs between each pair of contact elements. The dynamic case, with an elastic layer impulse response extending in time, is compared with the case where the corresponding quasi-static response is used. Results highlight the difficulty of estimating a constant contact stiffness as it increases during the indentation process between the elastic layer and the rough road surface. The stiffness–indentation relation additionally depends on how rapidly the contact develops; a faster process gives a stiffer contact. Material properties like loss factor and density also alter the contact development. This work implies that dynamic properties of the local tread deformation may be of importance when simulating contact details during normal tyre/road interaction conditions. There are however indications that the significant effect of damping could approximately be included as an increased stiffness in a quasi-static tread model.



## 1. Introduction

Numerical contact models are essential when optimising the complex tyre/road interaction process. This interaction has a wide range of implications, from rolling resistance and fuel consumption to traction and safety, wear of tyres and roads, and the generation of noise. Fundamentally such contact model includes the two interacting bodies, the road surface and the tyre tread, but the required level of detail and which aspects it must include is often ambiguous.

The tread cap is the outermost layer of the tyre structure providing comfort, traction, and resistance against wear. Standard tread material consists mainly of synthetic and/or natural rubber compounds forming a relatively soft, homogeneous, isotropic

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and almost incompressible material. Oils, vulcanising chemicals, and fillers such as carbon black and silica are typical substances added to change the material characteristics. Vulcanisation increases the shear modulus by increasing the number of cross-links between polymer chains and fillers. Fillers are used to further change properties, e.g. increasing the modulus while reducing the loss factor. This gives a less pronounced frequency dependence of the modulus compared with uncrossed-linked rubbers (e.g. natural rubber) that has clear terminal, plateau, transition and glassy zones. Generally, tread rubbers show stiffness and relatively large viscous losses that, within the normal working temperatures and frequency range of interest, slowly increase with frequency. More on tread materials can be found in e.g. [1].

In order to simulate tyre/road interaction there are two tread-related mechanisms that are important to consider. Firstly, how the tread influences the dynamic properties of the complete tyre. Secondly and what this paper is concerned with, how the local deformations of the tread in the contact zone affect the contact forces and contact geometry.

Few investigations in the literature seem to be directly focussed on the local deformation of the tyre tread. Kropp [2] made one of the first investigations on local deformation by measuring driving point mobilities using different excitation areas. Andersson et al. [3] experimentally and numerically studied the response of the tyre surface for different idealised tread patterns and excitation areas. It was observed that the local deformation can be of importance already in the lower frequencies for very small excitation areas. Numerical calculations were done with the model of two elastic layers developed by Larsson and Kropp [4]. This is one of the few tyre models that has also been demonstrated to capture the high-frequency (up to 4 kHz) response of the tread and in [3] it was shown that the model accurately captures the local deformation and handles excitation areas down to a few square millimetres. However, the model uses a plate geometry for the tyre structure and it is not able to provide the correct mode-shapes.

An inherent property of tyre/road interaction models is the spatial discretisation of the contact. Contact stiffness within an element, connected to the roughness profile within the element boundaries, can be assumed either infinite (Lagrange multipliers/no penetration condition), constant (linear contact springs) or nonlinear. The contact mechanics condition of no penetration at smaller length scales, i.e. below the resolution used in the discretisation, resulting in an infinite stiffness was used by e.g. Larsson [5,6]. A more common method to model the tread/road contact is to use a set of uncoupled springs with constant stiffness (e.g. [7–10]). An elastic half-space formulation has also been widely used for tyre/road contact (e.g. [11–13]) but also in classical contact mechanics (e.g. [14]). The uncoupled springs neglect the coupling of displacements within the tread. The elastic half-space includes the coupling but assumes infinite wave speed, i.e. the system reacts instantaneously everywhere. Neither one of these approaches includes the effect of inertia or losses within the tread when it is deformed. They also assume that the forces at the belt–tread interface are the same as on the tread surface. Another drawback is the difficulty in finding the single-valued stiffness of the bedding springs or the elastic half-space from the frequency-dependent Young's modulus and loss factor of the tread material. In practice, these parameters have instead to be tuned until correct static deformation is obtained [7,15]. By this procedure, the softening effect of small-scale road roughness is also included in an approximative way. Losses within the tread have been included in brush spring models by e.g. Liu et al. in [16]. In [17] they show that the contact force increases with indentation speed due to the tread rubber viscoelasticity. Another recent approach to include viscoelastic effects was presented by Dubois et al. [18]. Lopez Arteaga presented a 2D rolling resistance model in [19] where the tread dynamic was modelled using linear spring damper systems with frequency independent viscous damping. The model also included nonlinear contact springs to account for the small scale roughness of the road, first described by Andersson and Kropp in [20]. Effects of tread inertia are included in tyre/road interaction simulations that use finite element models. Fadavi et al. [21] calculated the forced response of a rolling tyre in contact with a flat rigid substrate. The response of loaded, rotating tyres was also modelled by Brinkmeier et al. in [22] and by Lopez Arteaga in [23]. However, finite element approaches are limited by their mesh size which affects both the frequency range of the results and the ability to capture local deformation. Sabiniarz [24], and more recently Hoever et al. [25–27] calculated the influence matrix for the contact problem from a detailed Wave Guide Finite Element model. Inertia and damping are in this way included in the description of the tread deformation. Linear contact springs were used in rolling simulations to account for the small scale roughness within an element. Hoever and Kropp [27] especially emphasised the influence of this stiffness parameter on the generated tyre/road noise. The absence of a straightforward way of deducing what the correct value of the spring stiffness should be was also stressed.

As the contact stiffness represents displacement of tread material, it will exhibit inherent mass inertia and damping characteristics. How important these dynamic features are will depend on the material properties, the spatial discretisation and the contact process itself. A discussion about the effects of tread mass and energy losses within the tread material is missing in many of the existing tyre/road contact models. As a consequence, the possible limitations due to these parameters are not fully understood.

The objective of the present work is to investigate the importance of including the tread dynamics in a tyre/road contact model. A numerical contact model is used for this purpose which simulates the detailed contact between an elastic layer and a patch of a rough road surface. The contact model was first presented in [20] where results were shown for an infinitely slow contact process with a quasi-static response of the tread. In the present paper the model is implemented on time dependent contact scenarios. Effects of tread inertia and damping are included by applying an elastic layer model similar to the one suggested by Larsson and Kropp [4]. The focus in the present work is on contact forces and contact stiffness over a small road patch and how these develop during the contact. Material parameters of the elastic layer are varied to examine the effect of inertia and energy losses.

The paper is organised as follows: the next section presents the numerical contact model that is used to simulate the interaction between the elastic layer and the road surface. Section 3 presents the cases studied and the input data used in