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Thermo-mechanically coupled investigation of steady state rolling tires by numerical simulation and experiment

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ABSTRACT

In this contribution, a numerical framework for the efficient thermo-mechanical analysis of fully 3D tire structures (axisymmetric geometry) in steady state motion is presented. The modular simulation approach consists of a sequentially coupled mechanical and thermal simulation module. In the mechanical module, the Arbitrary Lagrangian Eulerian (ALE) framework is used together with a 3D finite element model of the tire structure to represent its temperature-dependent viscoelastic behavior at steady state rolling and finite deformations. Physically computed heat source terms (energy dissipation from the material and friction in the tire–road contact zone) are used as input quantities for the thermal module. In the thermal module, a representative cross-sectional part of the tire is employed to evaluate the temperature evolution due to internal and external heat sources in a transient thermal simulation. Special emphasis is given to an adequate material test program to identify the model parameters. The parameter identification is discussed in detail. Numerical results for three different types of special performance tires at free rolling conditions are compared to experimental measurements from the test rig, focusing especially on rolling resistance and surface temperature distribution.

1. Introduction

Tires of passenger cars and trucks are complex, geometrically and physically non-linear structures of different components, mainly the rubber matrix and several cord layers which act as reinforcement. During their service life, tires are subjected to various mechanical and thermal loading scenarios (inner pressure, vertical and lateral forces, tire contact with curb or speed ramp, internal and external heat exposures) and undergo a certain alteration which leads in a consecutive phase to continuous and discontinuous deteriorations of parts of the tire or failure of the whole tire. The understanding of the tire's structural behavior to arbitrary load cases, characterized by a multi-axial stress state, is crucial for the design process which also includes more and more numerical analyses with respect to wear, fatigue and fracture (see e.g. [1–3]). In this context, the internal tire temperature plays an important role due to the fact that the mechanical properties depend on temperature and high temperatures can strongly accelerate chemical alteration processes which lead to material deterioration by changes in the rubber network structure. As a rule, the tire is subjected to a complex coupling mechanism of mechanical, thermal and chemical destructions during its service life, where the fatigue behavior at higher temperature is still under current research.

The temperature rise in tires is caused by dissipation of mechanical energy (dissipation in the rubber matrix, cords and their interfaces, irreversible material damage, friction in the tire–road contact zone) and external heat sources (heat loss of the engine and the braking system via the rim). The viscous dissipation of the rubber matrix can be identified as one of the main heat sources, especially under straight line free rolling. Cornering and braking maneuvers are directly linked to an additional heat generation, especially at the tire surface (tire tread) which is in contact with the road. These maneuvers can lead to a surface temperature increase which influences in the long term also the core temperature of the tire. The core temperature is mainly responsible for the mechanical behavior of the tire structure (e.g. stiffness of the tire to vertical loading), where the mechanical surface characteristics (friction coefficient, adhesion) of the tire are more linked to the surface temperature. As a result, the frictional behavior can be strongly influenced by the friction process itself without changing the structural behavior of the whole tire. Therefore, the performance of the tire depends strongly on its core and surface temperature.

Simulation methods: The simulation of tires is a challenging task. First, rubber shows non-linear elastic and inelastic properties

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which are in general rate- and temperature-dependent (e.g. viscosity, plasticity, Mullins effect, Payne effect), see e.g. Gent [4]. Second, reinforcing cords exhibit completely different material properties compared to the rubber matrix and lead to an anisotropic mechanical and thermal material behavior of the resulting composite structure. Third, local singularities (end of the cords, interface cord–rubber matrix) give rise to stress concentrations and potential failure locations. Fourth, the contact to the road and the rim demands for a contact formulation and, finally, the main operation mode is rolling which has to be incorporated into the simulation approach in an efficient manner.

The finite element method (FEM) has been intensively employed since the last decades to better understand the tire structure and to provide numerical design tools to tire manufacturers. The state of the art of tire simulation is summarized e.g. in Ghoreishy [5]. Finite element (FE) simulations are especially included into the design process since computer capacities are easily available to analyze large-scale structures in a short time. A major challenge is still to predict and quantify the property changes due to the damage mechanisms and to avoid an undesired degradation of the tire due to the mechanical and the chemical aging [6], where the latter demands also for an intensive physical–chemical research on polymers. Beside the application of the FEM to tires, other methods or semi-empirical approaches (model reduction methods) exist. These models are often simplified tire models of point masses or rigid body systems connected by springs and dashpots in order to characterize the tire's structural behavior, e.g. within the complex car–tire–road interaction by multibody dynamics. In this case, the focus is more on the overall structural behavior of the tire or parts of it. Such models (e.g. Magic Formula, TameTire, TMeasy, Hohenheimer Reifenmodell, BRIT, CDTire, FTire, SWIFT and RMOD-K to name only few of them) require primarily structural test data from the test rig (e.g. vertical stiffness and cornering stiffness) rather than detailed information about the tire compounds, their spatial distribution and their characterization via material tests.

To include the temperature prediction in the numerical simulation, different simulation approaches have been developed over the last few years by many authors. Beside the already mentioned simplified multibody models, the FEM plays an important role. In this case, one simulation strategy is the separate computation of (a) the deformation of the tire assumed as linear or non-linear elastic, (b) the derivation of dissipation and (c) the evaluation of the corresponding temperature. One advantage of this strategy is the easy implementation since no material history effects have to be considered. However, one drawback of this strategy is the computation of the dissipation which cannot be directly obtained from the mechanical analysis since the tire material is regarded as elastic. To overcome this drawback, several concepts have been developed to incorporate the viscoelastic properties of the rubber matrix in a simplified form.

Numerical investigations: Since the 1980s, thermo-mechanically coupled investigations of tires have been carried out by e.g. Sarkar et al. [7] for an approximated tire structure in 2D. A review on tire power loss models including different submodels for the constitutive material theory, the tire–pavement interaction, the thermal state of the tire and the model for the thermo-mechanical coupling is given in Whicker et al. [8]. Beringer et al. [9] studied the sensitivity of tire temperature to heat generation in tire compounds by an 1D heat transfer model and a simplified tire geometry. In Ebbott et al. [10], a coupled thermo-mechanical method is demonstrated in which the stiffness and the loss properties are functions of the current strain, temperature and frequency state. Clark and Dodge [11] analyzed the heat generation of aircraft tires which undergo large deformations due to high vertical loads in combination with high velocities. A one-way coupling approach has been suggested by Yavari et al. [12] to take into account heat source terms arising from dissipation and friction by a simplified model of the complex and non-linear tire system. Luchini et al. [13] focused on the tire rolling loss computation by an advanced strain-based material model by using the directional incremental hysteresis theory. The sensitivity of the elastic tire response to changes of the material's stiffness has been assessed by Futamura and Goldstein [14] to propose a model which is based on simple algebraic expressions to relate the dissipation to the local temperature. Park et al. [15] presented a modular concept (deformation, dissipation, thermal module) to investigate steady-state rolling tires, where the dissipation has been obtained by an analytical method based on the theory of viscoelasticity. Narasimha et al. [16] proposed an approach for the thermo-mechanical iterative investigation of non-axisymmetric tires with tread patterns by a Petrov–Galerkin Eulerian technique formulated in cylindrical coordinates. Recently, Wang et al. [17] published a parametric study for the highest shoulder temperature of steady state rolling tires by using a modular simulation approach.

However, in most of the cited references, the mechanical behavior of the tire is assumed as elastic. For standard Lagrangian analyses, several sophisticated material models for coupled thermomechanics exist which take also into account thermal behavior, damage and finite viscoelasticity, e.g. by internal variables and evolution equations in the time domain. Such material models have been proposed by e.g. Miehe [18], Holzapfel and Simo [19], Reese and Govindjee [20], Boukamel et al. [21], Behnke et al. [22] in combination with different solution schemes, see e.g. Armero and Simo [23]. However, the major problem has been their incorporation into the simulation approach of rolling tires for which the Arbitrary Lagrangian Eulerian (ALE) framework is the most applied technique (see e.g. [24]). In this case, the material history of the inelastic material has to be correctly incorporated into the numerical simulation approach which is directly linked to the transport of the material through the FE mesh. In this context, Suwannachit and Nackenhorst [25] presented recently a novel approach for the thermo-mechanical analysis of steady state rolling tires including a viscoelastic model for the rubber material at finite deformations. The coupled balance equations are solved with the help of an isentropic operator-split algorithm incorporated into an ALE relative kinematic framework, i.e. mechanical and thermal solution fields are exclusively computed on one 3D FE model of the tire with at least four degrees of freedom per node.

Experimental investigations: Not only the numerical models have to be correctly set up, but also their input and model parameters are of significance. Therefore, intensive research has been carried out based on the experimental characterization of the tire behavior with respect to temperature, heat generation and heat exchange. Experimental investigations with respect to the emissivity of rubber, applied to e.g. the tire tread and the sidewall, are performed in Browne and Wickliffe [26], where the consequences for the thermal modeling are discussed. For rolling tires, the dynamic heat exchange involving complex aerodynamic considerations is important as well. Numerical simulations and experimental studies on these topics have been carried out by Kato et al. [27] who investigated the surface geometry of the tire's sidewall in order to advantageously reduce the tire temperature during rolling operations. Oh et al. [28] investigated the internal temperature distribution in a tire by transformation to simple computational domains in combination with experimental infrared (IR) measurements. In LaClair and Zarak [29], the influence of the test setup (flat surface or drum) for truck tire endurance testing with respect to the temperature evolution is discussed, where the influence of a flat or a curved surface is highlighted.