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Original articles

Thermo-mechanical coupled finite element simulation of tire cornering characteristics—Effect of complex material models and friction law

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Highlights

- An advanced thermo-mechanical finite element model for radial tires was developed.
- Temperature dependent material properties was used with complex frictional law.
- Cornering behavior was tested on a flat-trac machine and compared with predicted data.
- Effects of temperature dependent material model, friction law and caster angle were investigated.

Abstract

This research work is devoted to the development of an advanced finite element model for the simulation of a rolling tire under cornering conditions. The main goal of this research is to investigate the effect of material and frictional models complexity on results accuracy. A finite element model based on a coupled thermo-mechanical procedure was developed using Abaqus and two specific in-house user subroutines called as FRIC and UMASFL were written. Simultaneous consideration of real frictional behavior in conjunction with temperature dependent hyper-viscoelastic materials properties was performed. The accuracy of simulations with different complexity levels were checked via comparison between simulation results and the obtained data from a tire tested on a flat-trac machine. The results showed that the frictional heat generation during tire cornering is really complicated and could not be described with available models. Parametric studies revealed that the generated lateral force was not affected considerably by model complexity, but the aligning moment and pressure distribution in footprint area were very sensitive to the model complexity level.

Keywords: Tire; Finite element method; Thermo-mechanical; Friction; Cornering

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1. Introduction

Pneumatic tires are important components in a vehicle which play a key role in determination of its performance. For example, fuel consumption and energy saving, ride and handling as well as safety are significantly dependent on tire performance. Over the past decades there have been extensive researches on the development of computational methods for the analysis of tires under various loading conditions [15]. However, these models do not take into account the highly complicated features of a rolling tire such as its highly nonlinear inelastic behavior, time dependent and randomly applied loads, complex wear and frictional behavior at contact area and etc. Consequently, the development of advanced models aimed at addressing the complex aspects of tire modeling that have not been yet considered. Several researchers tried to determine and minimize the errors between the data obtained by experimental methods (indoor and outdoor) and the results achieved by numerical techniques such as finite element method (FEM) [3,19,34]. One of the main indoor experiments that is vastly used to evaluate tire behavior is the flat-trac test in which forces and motions are applied to a tire running on a continuous flat belt [28]. This allows the user to study how a specific tire design affects vehicle dynamics. Accurate simulation of this test can lead to a reduced design cycle time and costs.

The main goal of this research is to investigate the effect of material and frictional models complexity on cornering test simulation results accuracy. It was tried to fill the gap between current tire simulation strategies and the actual situation in a tire cornering experiment by taking the non-isothermal temperature dependent behavior of rubber compounds and the complex frictional conditions between tire and the contact surface. For achieving this purpose, an advanced thermo-mechanically coupled finite element model has been developed to simulate the cornering of passenger car tire on flat-trac machine. Computer simulations were carried out using Abaqus standard command line in conjunction with in-house developed FRIC and UMASFL user subroutines. These two specific in-house user subroutines were written for the inclusion of complex frictional behavior between tire and road and also convection–diffusion heat transfer inside the tire consequently. In order to show the capability of this methodology and the effect of model complexity level on results accuracy, several parametric simulations were done and the results were compared with experimental data obtained from a tire tested on the flat-trac machine. To the best of our knowledge there is no comprehensive study on the finite element simulation of tire cornering behavior that considers all important influencing factors including temperature dependent material properties and complex frictional behavior simultaneously and also evaluates the simulation results with experimental data.

In the following sections, a brief overview on the history of the cornering behavior simulation of steady state rolling tires is given at first. Then, the non-isothermal rolling theory that is the combination of the heat transfer analysis and rolling of tires in conjunction with nonlinear frictional model is described. Subsequently, the development of the finite element model for a P185/65/R14 tire is concerned. In this part, generation of a converged mesh, determination of material model parameters as well as the adopted computational strategy is investigated in detail. The tire experimental and computer simulation results, their comparison with each other and discussion on the findings are given in the subsequent sections.

2. Historical background

One of the first attempts for the computer simulation of a tire under cornering loads was carried out by Gardner and Theves [13]. They modeled the cornering tire quasi statically using a nonlinear geometric approach by applying the lateral force and slip angle to the spindle of the wheel. Other researchers tried to enhance this simulation by using different mathematical approaches and more complex geometrical models. Koishi et al. [22] and Kabe et al. [21] investigated the effect of implicit and explicit simulation approaches on the results accuracy. Based on their founding the computed cornering force with both implicit and explicit methods agreed with experimental data and the only considerable difference is much longer analysis time for the explicit approach. However, their proposed model was very simple and the results deviated from experimental data at medium slip angles. A considerable amount of literature has been published on cornering behavior simulation. Most of these studies have tried to enhance the simulation accuracy with improving the mathematical aspects of the adopted finite element method [9,33] and some of them have investigated the effect of tire structure on produced force and moments during vehicle cornering [17].

Recent researches on rolling tire simulation have been focused on the provision of more accurate frictional contact models. Tire road friction could be considered as the heart of tire dynamic and any model could not provide a precise picture of the tire dynamics without accurate friction law. The above mentioned simulations were done by using simple phenomenological contact frictional models, e.g. the Coulomb friction law, that is failed to calculate lateral force and