

Finite Element Modeling of Tire Transient Characteristics in Dynamic Maneuvers

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ABSTRACT

Studying the kinetic and kinematics of the rim-tire combination is very important in full vehicle simulations, as well as for the tire design process. Tire maneuvers are either quasi-static, such as steady-state rolling, or dynamic, such as traction and braking. The rolling of the tire over obstacles and potholes and, more generally, over uneven roads are other examples of tire dynamic maneuvers. In the latter case, tire dynamic models are used for durability assessment of the vehicle chassis, and should be studied using high fidelity simulation models. In this study, a three-dimensional finite element model (FEM) has been developed using the commercial software package ABAQUS.

The purpose of this study is to investigate the tire dynamic behavior in multiple case studies in which the transient characteristics are highly involved. The process of running dynamic FE tire simulations starts by statically inflating and loading the tire using an implicit method with refined mesh in the contact patch. Then, by using the result transfer option, final state vectors are used as initial conditions for subsequent simulations. Using this sequence of loading steps helps increase the efficiency of the code.

The validation of the model is performed in two stages. First, tire mode shapes and associated natural frequencies and damping values are compared with the experimental data. Second, a series of transient dynamic simulations are performed using an explicit method with a fine mesh around the circumference of the tire. Finally, the FEM model results are filtered to eliminate the numerical noise, and their correlation with the test data is investigated. Moreover, the effect of the normal load on spindle forces features such as peak values and time shifts are studied. The results show that the tire dynamic response is autonomous.

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INTRODUCTION

During the design stage of the tire and car components that are directly influenced by tire behavior, such as suspension, different loading scenarios should be considered. Based on the type of loading inputs and tire boundary conditions, the tire presents a static, quasi-static, steady-state dynamic, or transient dynamic behavior. Among these, due to their impulsive force and moment characteristics, transient responses of the tire are the main focus of this study.

The finite element method is chosen as the framework for modeling the tire nonlinear system. This method allows modeling detailed geometrical and material properties of the tire, which can encompass time and frequency dependent material characteristics. Incorporating this approach can be a substitute for physical tire evaluation process which is time consuming and is cost effective by its nature [1]. Additionally, compared to empirical and semi-empirical tire models for which the accuracy is highly dependent on the parameterization

procedures and test conditions, finite element models once parameterized using geometrical and material properties, can be used in a wide variety of testing conditions [2].

The assessment of tire transient behavior using FEM has been conducted by many researchers. For analysis of flexible pavements that are subjected to dynamic loads, Zaghoul [3] introduced a 3D model in ABAQUS, and validated the model using static and dynamic case studies data. The effect of the tire vibrations, induced by road irregularities, on the vehicle comfort quality was studied by Scavuzzo [4] using a validated model. Zachow [5] used a discrete 3D membrane shell dynamic tire model for vehicle ride analysis in the frequency range of 1000 Hz and beyond. Kao [6] developed a FEM tire model with LSDYNA3D and studied the spindle longitudinal and vertical forces during the impact of the tire with semi-circular cleats. His research was extended for six additional impact case studies by Kamoulakos [7] and demonstrated an instability-free algorithm developed in PAMSHOCK. Mousseau

[8] developed a simple 2D membrane tire model to predict spindle forces during impacting large obstacles. Furthermore, the transient response of the treaded tire to small cleat impacts is analyzed by Cho [9] through an explicit method.

In this study, we construct a finite element model for studying the tire transient dynamic behavior for dynamic maneuvers such as traction, braking, and cleat negotiation. The importance of this research is that it considers a detailed FEM model for the tire sections, which includes different tire hyperelastic, viscoelastic, and elastic material properties. Additionally, a hybrid explicit/implicit approach is conducted to reach the final dynamic results more efficiently. More importantly, the experimental modal analysis and cleat test data are used to assess the validity of the developed FEM tire model.

The tire used in this study is a Michelin 205/55 R16 90, from the Tyre Model Performance Test (TMPT) program. A hybrid implicit/explicit approach is chosen to assure model convergence. This method uses an implicit approach for initial stages, such as inflating, loading, and steady-state rolling of the tire. This makes the run time for reaching the transient simulation initial conditions, such as tire velocity, independent of the initial conditions. Therefore, at the end of the steady-state stage, the final state-vector of the tire elements, which is the output of the model state-space solver and contains nodal information such as position, velocity, and forces, is used as the initial condition for transient simulation.

To verify the model under steady-state conditions, modal analysis test is conducted, in which tire mode shapes, natural frequencies and damping values are extracted and are compared to the simulation results. As for tire dynamic behaviour, a series of transient maneuvers are performed to study abrupt state changes of the system. In these tests the tire forces are compared with experimental data in order to evaluate the validity of the model. Additionally, the effect of the loading on spindle forces properties is evaluated in detail.

MODELING THE TIRE STRUCTURE

The finite element modeling starts with importing the geometrical properties of the system into the software. The cross sectional data from the Tyre Model Performance Test (TMPT) is used for constructing the tire cross-section model in Solid Works, as shown in Figure 1.

The TMPT program introduces a standard set of test procedures to evaluate the performance of the tire models in conjunction with MBS vehicle models. Tests are divided into model capability tests and validation tests. The capability tests are designed to study the qualitative behavior of the tire, and show the physical plausibility of using the model. The validation tests contains the experimental test results for some steady-state and dynamic measurements [10]. It should be noted that

similar definitions and arrangements for principal axis and force measurements are considered as the basis for constructing the current FEM model.

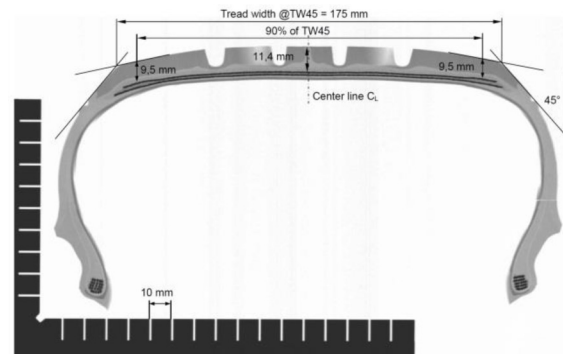


Figure 1. Cross Section of the tire front tire model performance test

In this study, to keep the model relatively simple, the detailed geometrical sections of the tire, such as grooves, and sipes were not considered [11]. Next, the CAD model is transferred to Abaqus/CAE for material assignment and for creating the axisymmetric model from the tire cross-section, as presented in Figure 2. The developed model represents the structure of the actual tire that consists of tread, sidewall, carcass, belt, bead, filler, etc. The sidewall, apex, inner liner, and tread are made of rubber with different properties. Additionally, the carcass, belts, and beads are reinforced composite materials with single or multiple layers of reinforcements [12].

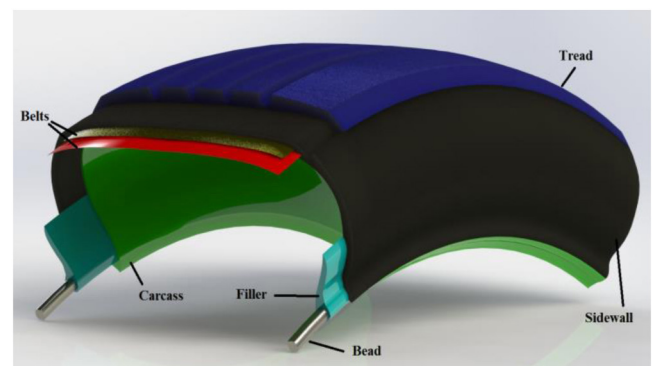


Figure 2. Developed CAD model in Solid Works transferred to ABAQUS for FEM analysis

Information about tire material properties, processing, mixing, assembly, and curing are often confidential, and cannot be received from tire companies. Furthermore, the material properties for the same tire from a manufacturer may vary, due to the vulcanization process, for example. The parameterization for individual materials in the tire requires a set of experimental and analytical procedures, such as tension and relaxation length tests, on individual tire sections. Based on this initial analysis, the appropriate material model is chosen and related model coefficients are obtained using data curve fitting. Due to the fact that performing the entire parameterization procedures is out of the scope of this project the available data from previous studies that conducted for similar tires have been used in the current model [10, 13, 14].

15, 16, 17]. The main material properties used in ABAQUS to construct the structure of the tire are listed in Table 1, Table 2, and Table 3. In order to reach a reasonable match between the experimental data and simulation results, some of the material properties values are modified accordingly.

Table 1. Hyper-elastic properties

Rubber material	C_{10}	C_{01}	Density (kg/m ³)
Tread	805 kPa	1.8 Mpa	1180
Sidewall	170 kPa	845 kPa	1100
Ply	140.32 kPa	390 kPa	1190
Belt	15.33 MPa	20.45 MPa	1200

Table 2. Viscoelastic properties

Rubber material	Relaxation modulus (g)		Relaxation time (sec)	
Component	G_1	G_2	τ_1	τ_2
Tread	0.1254	0.0921	6.5122	226.7531
Sidewall	0.1597	0.07043	5.9709	243.7300
Ply	0.0934	0.08231	20.8027	350.3403
Belt	0.16832	0.07223	5.9642	204.0324

Table 3. Elastic Property for reinforcements

Reinforcement	Young's modulus (N/m ³)	Poisson's ratio	Density (kg/m ³)
Bead	1.99283 E11	0.31	7490
Ply	5.01275 E9	0.5	1050
Belt	2.17826 E11	0.3	7500
Chaffer	1.725 E9	0.5	940

Hyperplastic Material

The rubber components are modeled using Mooney-Rivlin theory of hyperplastic materials, which is based on the rubber strain energy. The strain energy density function with first and second strain invariants can be expressed as follows:

$$W = C_{10} (\bar{I}_1 - 3) + C_{01} (\bar{I}_2 - 3) \quad (1)$$

Where C_{10} and C_{01} are experimentally determined material constants, and $\bar{I}_1$ and $\bar{I}_2$ are the first and second invariant of the unimodular component of the left Cauchy-Green deformation tensor, and can be identified as [16]:

$$\bar{I}_1 = \bar{\lambda}_1^2 + \bar{\lambda}_2^2 + \bar{\lambda}_3^2 \quad (2)$$

$$\bar{I}_2 = \bar{\lambda}_1^{(-2)} + \bar{\lambda}_2^{(-2)} + \bar{\lambda}_3^{(-2)} \quad (3)$$

The $\bar{\lambda}_i$ is the deviatoric stretch that is defined as:

$$\bar{\lambda}_i = J^{-\frac{1}{3}} \lambda_i \quad (4)$$

Here J is the total volume ratio and λ_i is the principal stretch that is expressed as:

$$\lambda_i = 1 + \varepsilon_i \quad (5)$$

In which ε_i is the principal strain. It should be noted that in these formulas for incompressible and isothermal materials, $J = 1$ and $\lambda_1 \lambda_2 \lambda_3 = 1$ [18].

In ABAQUS, the hyperplastic elements with reduced integration and hourglassing control are chosen for avoiding shear locking and hourglassing in simulations. The shear locking happens when a FEM block undergoes bending and consequently cannot follow the curved shape. This makes the strain energy of the element produce shear deformation instead of bending deformation [19]. The reduced integration method which is used for controlling the shear locking suffers from its own numerical difficulty which is called hourglassing. When hourglassing happens, a zero-energy mode is produced in response to bending loading that can propagate when a coarse mesh is used and makes the elements excessively flexible.

Viscoelastic Material

In order to properly simulate the transient behavior, the tire model with basic hyperplastic property should be enhanced by incorporating its viscoelastic property. This property is a function of time and frequency which can be related to rolling resistance and internal damping of the tire. In this study we consider the time dependency of the viscoelastic property by using a version of the dimensionless relaxation modules expansion, called Prony series:

$$G(t) = G_0 - \sum_{i=1}^N G_i [1 - e^{(-t/\tau_i)}]$$