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Research Paper

Transient dynamic behaviour of finite element tire traversing obstacles with different heights

Chongfeng Wei *, Oluremi Ayotunde Olatunbosun

School of Mechanical Engineering, University of Birmingham, Birmingham B15 2TT, UK

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Abstract

Tire models used in vehicle dynamics simulation for CAE durability and ride comfort assessment need to be capable of predicting the non-linear deformation and enveloping characteristics which occur when traversing large road obstacles. Normally, transient dynamic characteristics of a rolling tire are determined from tire rig tests, and the tire parameters are transferred into multi-body system for vehicle dynamic analysis. However rig design limitations mean that tests cannot be carried out in the most severe conditions, particularly for traversing high ramp or large obstacles. However, using detailed FE tire models, such tests can be carried out virtually. A FE tire model was developed specifically for this purpose using explicit integration in ABAQUS™. Tire enveloping tests in traversing obstacles of different sizes were then carried out, virtually, using the validated FE tire model. Satisfactory results of transient responses were obtained by comparison with the experimental tests for the tire traversing obstacles with different heights. Tire transient dynamic behaviour was investigated by analysing the influence of tire rolling velocity and height of road obstacle on transient spindle responses, dynamic stiffness, together with tire deformation for the tire impacting obstacles. Finally, the investigation showed that longitudinal dynamic stiffness decreases when the tire traverses a higher obstacle. In addition, with the increase of height of road obstacle, the resonant amplitude of spindle force response as well as the tire deformation becomes larger in both longitudinal and vertical directions, especially for the tire rolling over 25 mm × 25 mm rectangular obstacle. Also, it is found that higher travelling velocity of the tire leads to higher resonant amplitude of spindle forces in the vertical direction.

Keywords: Transient dynamics; Road obstacle; Explicit program; FE tire model

1. Introduction

As a unique component of the vehicle connecting road and the car body, tires play an important role in reducing the effect of road irregularities by attenuating the forces transmitted to the vehicle suspensions. It is of great importance to accurately predict the transient dynamic behaviour of the tire in traversing large obstacles under different operating conditions, in order to provide tire designers and researchers with a fundamental understanding of aspects of tire behaviour in ride comfort assessment and vehicle durability analysis under such extreme tire/obstacle interaction. Therefore, tire models used in CAE vehicle dynamics simulation for durability and ride comfort assessment need to be capable of predicting the non-linear deformation and enveloping characteristics which occur when traversing large road obstacles.

However, there are great challenges for predicting the transient dynamic responses of the tire traversing obstacles with acceptable accuracy in the numerical simulations because of the difficulties arising from modelling

* Corresponding author. Address: School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK. Tel.: +44 (0)121 414 4167.

E-mail address: cxw103@bham.ac.uk (C. Wei).

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complexities of the tire. One of the problems is the definition of the geometric (structural layup) and material properties of the tire, which are of significance for the tire modelling. The construction of the steel belts and the hyperelastic and viscoelastic properties of the rubber components are significant elements to be considered in the construction of the tire model. In addition, a reliable analytical or numerical approach is needed to analyse the transient dynamic behaviour with suitable efficiency and accuracy. Another problem is that the rolling tire traversing obstacles will lead to a large deformation of the tire when impacting the cleats, associated with large-scale longitudinal frictional dynamic contact, which is yet another contributor to the complexity of the tire model.

Due to the complexity of the tire/obstacle impacting problem and limitations in numerical techniques for predicting transient dynamic behaviour of rolling tires, experimental approaches were developed for estimating the tire enveloping characteristics at low speed and transient dynamic properties of tire rolling over obstacles for different types of tires [1,2]. Although most of the simple tests can be carried out for investigating the tire transient dynamic property, some severe conditions could not be conducted because of the limitations of laboratory facilities, particularly for large obstacles and road unevenness. In addition, tire transient dynamic analysis using experimental methods is an expensive work for engineers, as different types of tires and different kinds of road obstacles need to be adopted in the tests.

Based on the existence of these problems, some analytical tire models were developed to predict the transient dynamic responses of rolling tires. Bandel and Monguzzi [3] developed a "black box" mathematical tire model on the basis of experimental test results for studying a tire running over an obstacle at low speed and high speed respectively. Low-speed forces could then be obtained by using the empirical relationships, while the high-speed forces were derived by using the low-speed forces at the hub as the input to an oscillating system with one degree of freedom. Guan and Fan established an analytical tire model derived from experimental modal parameters below 350 Hz extracted from the radial and tangential responses under radial and tangential excitation. With consideration of the nonlinear stiffness of tire sidewall, a quantitative inplane rolling tire model was developed to investigate tire dynamic responses and enveloping properties when the tire rolls over different cleats with different values of inflation pressure and wheel load in the time domain and frequency domain respectively [4,5]. The SWIFT model was another analytical tire model developed by the Delft University of Technology in cooperation with the TNO Automotive [6,7]. The model is capable of predicting road obstacle enveloping properties in the condition of relatively short wavelength (0.1–0.2 m). The SWIFT tire model is composed of four main independent elements: Magic Formula, contact patch slip model, rigid ring, and obstacle enveloping model. The belt and carcass in the model are approximated as a rigid ring that is attached to the wheel rim through flexible sidewalls. The Magic Formula model is used as the basis for generating nonlinear contact forces and moments. However, these analytical models could not effectively predict the influence of tire material properties and structural layup on the tire dynamic behaviour.

In order to meet the requirements for parametric study and consideration of acceptable accuracy, several researchers and engineers developed FE tire models to carry out transient dynamic simulations for tire traversing obstacles. Mousseau and Hulbert developed a simple and efficient model that could predict spindle forces produced by the tire impacting a large obstacle accurately. Due to the inaccuracy and simplicity of simplified models like the radial spring and terrain models, they developed the tire model by using an inextensible, circular membrane in combination with an elastic arch to approximate the sidewall behaviour, while the tread was modelled by using a geometrically nonlinear beam element [8–10]. However, while the tire model is applicable for vehicle dynamics simulation with the capability of analysing durability events, it is unable to provide sufficient parameters information for the tire designer due to the simple construction of the tire model. In order to accurately describe the process of tire impacting a cleat, Cho et al. developed a 3-D tire model with detailed tread pattern definition for transient dynamic response analysis of a rolling tire impacting with a small obstacle with the width of 50.8 mm and the height of 12.7 mm, in which, the total Lagrangian formulation and the penalty method were applied to deal with frictional dynamic contact problem [11]. Kamoulakos and Kao developed the finite element approach using PAM-SHOCK™ for studying the transient dynamic properties of a rolling tire impacting a road imperfection. In their study, the influence of impact between a rolling tire and a spinning drum with road imperfection was examined numerically using explicit time integration scheme. Up to 21 tire revolutions were simulated to demonstrate the reliability and stability of the program in resolving tire impacting problems [12]. Olatunbosun and Burke used MSC/NASTRAN™ to develop a time domain rotational FE tire model for the study of the dynamic performance of a 195/65 R15 radial tire traversing a small cleat, in which the tire carcass was represented by laminated anisotropic shell elements as it was capable of defining the non-linear material properties and had satisfactory computational efficiency, while the rigid wheel was represented by beam elements [13].

Numerical simulation of tire transient dynamic properties is definitely a time consuming work because of the refined meshes of the tire in the contact area and complex numerical technique for resolving the frictional dynamic contact problem. However, the improvement in computer performance, the development of FE software and the optimization of the tire model, associated with the advances of numerical algorithms, are providing favourable opportunities to carry out numerical simulations of transient dynamic properties when the tire traverses road obstacles.