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The effects of tyre material and structure properties on relaxation length using finite element method

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ABSTRACT

This study investigates the influence of tyre structural layup and material properties on the relaxation length of a rolling tyre using finite element analysis. Relaxation length for rolling tyre under different operating conditions has been studied recently. However, the effects of tyre structural layup and material properties on relaxation length were ignored. In this present work, a finite element (FE) tyre model was built based on the material and geometry properties obtained from measurements of the tyre provided by a vehicle company. Rather than the common method (steady state rolling analysis) used for cornering behaviour simulations, ABAQUS/Explicit program was used for prediction of the cornering performance and relaxation length for a constant slip angle of the rolling tyre. Two different steer inputs were applied to the rolling tyre in terms of slip angle variation, namely step input and ramp input. The effects of various factors, including cross-section area, spacing, crown angle and strength of the tyre reinforcement cords, on relaxation length of the rolling tyre were investigated by numerical experiments using the design of experiment (DOE) method.

1. Introduction

Tyre characteristics during a dynamic change of wheel motion conditions have been concentrated on by engineers within the last two decades. It is well known that tyre lateral deformations do not occur instantaneously when a steering angle input is applied on it. The time delay of the lateral force response resulting from tyre lateral deformation is an important transient tyre property. Relaxation length is a property of a pneumatic tyre that describes the delay between when a slip angle is introduced and when the cornering force reaches its steady state value. Normally, relaxation length is defined as the rolling distance needed by the tyre to reach 63% of the steady state lateral force.

Relaxation length is an important factor for vehicle handling response. The shorter the relaxation length of a tyre, the more responsive its handling performance. Understanding the relaxation length behaviour of a rolling tyre can help to improve the simulation of vehicle handling performance. Tyre relaxation has been observed in the laboratory conditions through dynamic test methods [1–3].

Due to the influence of tyre behaviour on vehicle handling, it is necessary to implement accurate tyre dynamic models in vehicle handling simulation for predicting vehicle dynamic responses to different steering input functions. Therefore, accurate prediction of the tyre's relaxation length and its implementation in the tyre dynamic model is of great importance in accurate simulations of vehicle response to steer inputs.

Maurice and Pacejka [2] determined the relaxation length from frequency response functions and step responses of a non-linear tyre model. In their simulations, the contact force and moment were generated by a tyre/road contact brush model. To improve the accuracy of the relaxation length, the lateral force responses of the model with an increment of the slip angle had to be fitted with an exponential function. Loeb et al. [4] used a first-order differential equation to describe the time varying lateral displacement of the tyre tread and, hence, to derive the relationship between the time and the lateral force since lateral force is directly proportional to the lateral displacement of the tread. However, this tyre model developed by them is only valid for small slip angles. Rill [5] also used first order differential equations to approximate the dynamic reactions of the tyre lateral forces and torques to disturbances, and the first order approximation was written as [5]

$$F_y(v_y+\dot{y}_e)\approx F_y(v_y)+\frac{\partial F_y}{\partial v_y}\dot{y}_e \tag{1}$$

where F_y represents the lateral force, v_y denotes the tyre lateral velocity, and the lateral tyre deflection Y_e was also taken into account. Based on his derivation, the relaxation length for the lateral tyre deflection was expressed as a function of the wheel load and the slip angle. Mabrouka et al. [6] developed a steering system model to investigate the transient responses to steering torque input, in which the lateral flexible tyre model was built to predict lateral forces, but the prediction of transient responses was valid only for small slip angles.

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There are very few studies reported in the literature which have been concentrated on the prediction of relaxation length using the finite element (FE) method although the FE method is now routinely used for various aspects of tyre static and dynamic analysis. Finite element analysis has the advantage of facilitating the investigation of the effect of tyre material and structural properties on tyre behaviour and is widely used by automotive engineers and tyre designers [7–10]. Some typical examples are: Yang et al. [11,12] who investigated tyre durability properties based on the variations in carcass ply turn-up and bead reinforcement turn-up using FE method; Behroozi and Olatunbosun [13] who conducted a study on the influence of FE model complexity on aircraft tyre performance characteristics; Mohsenimanesh et al. [14] who developed a nonlinear and multi-laminated tractor tyre model to investigate the pressure distribution of an off-road tyre; Guo et al. [15] who developed a detailed aircraft finite element tyre model for dynamic simulations of tyre loading upon aircraft landing scenarios using rubber and fabric material properties which were characterised and correlated.

This paper presents an approach for prediction of relaxation length using a developed FE tyre model. Detailed description of the rubber material property definition and tyre structural layup definition are presented in the FE tyre model development. In this study, the relaxation length derivation is based on prediction of the transient dynamic behaviour in the time domain using Abaqus/Explicit program. The transient dynamic analysis has been applied by Wei and Olatunbosun [16] in investigating the tyre performance when impacting large obstacles. Cho et al. [17] also analysed the transient dynamic responses of 3D patterned tyre rolling over a small cleat fixed on a drum. Koishi et al. [18] used the explicit FE analysis code PAM-SHOCK to conduct cornering simulations, in which the fiber-reinforced rubber composites were modelled with multi-layered shell elements. Rao et al. [19] discussed the simulation of combined cornering-cum-braking behaviour of a pneumatic tyre by use of the explicit finite element code. Different from the transient dynamic analysis in the literature [16–22], two different inputs are applied to steer the rolling tyre.

2. Finite element tyre model

The 2D tyre model was built based on a 235/60 R18 tyre product, in which the rubber materials are composed of tread component, sidewall component and apex component, and the reinforcements are embedded in these rubber materials. The 2D FE tyre model is illustrated in Fig. 1. The definition of the structural layup of the reinforcements, together with rubber material properties are described in the following sections. In order to achieve an accurate geometry model, the 2D tyre cross-section was extracted from a real tyre product and the geometric shape was captured using a digital camera.

2.1. Structural layup of reinforcements

As is well known, the tyre consists of different reinforcements which are embedded in rubber component in the form of layers. Different reinforcement components with different characteristics are positioned in rubber material. Rebar elements in ABAQUS are able to define the structural layup for different layers in membrane and surface elements. Cord spacing, cord cross-section area, cord orientation inside a ply and cord material property are all necessary parameters for definition of the structural layup of reinforcements. A schematic representation of reinforcement components is shown in Fig. 2, where the orientations of the cords are given.

The area of cord cross-section can be obtained by measuring the diameter of the reinforcement using micrometer gauge as shown in Fig. 3. The spacing between the centre of the two neighbouring cords and orientation can be easily obtained using image processing techniques (Fig. 4).

Measurements of the structural characteristics for different reinforcements were carried out and the test data are shown in Table 1.

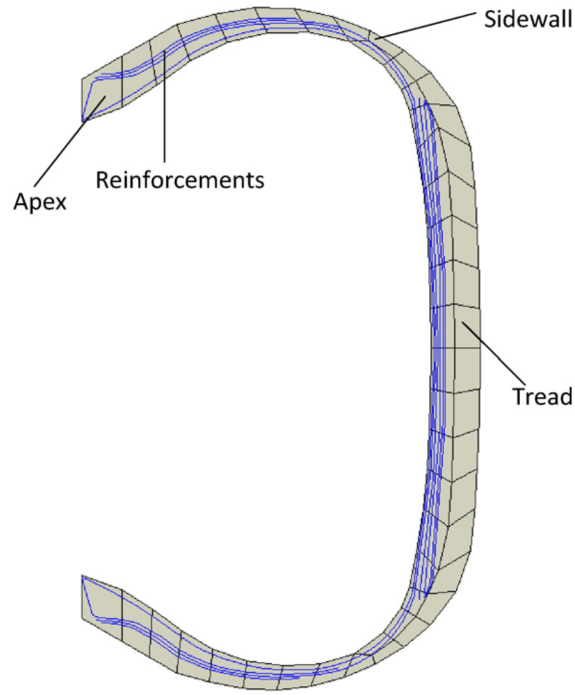

Fig. 1. 2D FE tyre model.

2.2. Material property definition

Material properties of the rubber material were defined by combining the tests and evaluation using existing material models. Because of the limited support from tyre manufacturers in supplying material samples, rubber samples were separately extracted from the tread, the sidewall, and the apex sections of a tyre product. Normally, the tensile test sample should be better extracted as a dumbbell or ring shaped specimen. However, because of the narrow sections of rubber in a tyre product, it is not realistic to acquire either a dumbbell or a ring specimen from it. In this study, some straight narrow strip rubber specimens were prepared for testing. These specimens satisfy the ASTM-D412 requirements [23] for test specimens. In this case, the length of the test sample needs to be more than 10 times longer than its width and thickness so it can produce the same reliable test data as the other two shaped samples in hyperelastic property test of rubber.

The uniaxial extension method was applied to carry out the hyperelastic property test of the rubber components [12]. The temperature for the test was set as the common room temperature (about 23 °C) according to the standard in ASTM-D412 [23], and the rubber samples were stretched for more than ten pre-conditioning cycles until the stress/strain relationship becomes stable prior to data collection. For the formal tests, the uniaxial procedure is repeated at least three times in order to obtain a realistic average test data.

Due to the accuracy and ease of application of the Yeoh material model, it was chosen to define the hyperelastic property of the rubber components by fitting the uniaxial extension test data. The expression of the Yeoh model is shown as

$$U = C_{10}(I_1-3) + C_{20}(I_1-3)^2 + C_{30}(I_1-3)^3 + \frac{1}{D_1}\left(J^{el}-3\right)^2 + \frac{1}{D_2}\left(J^{el}-3\right)^4 + \frac{1}{D_3}\left(J^{el}-3\right)^6 \quad (2)$$

where U represents the strain energy density; $C_{i0}(i = 1, 2, 3)$ and D_i $(i = 1, 2, 3)$ are material constants which describe the shear behaviour and material compressibility respectively, and are to be determined by testing and test data fitting in ABAQUS; J^{el} is the elastic volume ratio,