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Thermo-mechanical coupling analysis of transient temperature and rolling resistance for solid rubber tire: Numerical simulation and experimental verification

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A B S T R A C T

The achievement of low rolling resistance and long-term durability of tires on various vehicles is of great challenge. Tire performances heavily depend on rubber properties; however, the thermo-mechanical coupling characteristics of rubber composites are complicated rendering the design of high-performance tires time-consuming and costly. In our research, the transient temperature and rolling resistance of a solid rubber tire were performed based on the thermo-mechanical coupling approach and nonlinear viscoelastic theory by using finite element method. Particular attention was paid to the strain cycles as the tire rolling on the road presents non-sinusoidal deformation. First, a static three dimensional tire-road contact analysis was conducted to obtain the principal strain cycles. Second, the 100th-order Fourier sine series was used to approximate the strain amplitude. Third, the heat generation rate proportional to the product of the loss modulus and the square of strain amplitude was calculated. The loss modulus was updated as a function of strain amplitude, temperature and frequency. Loss modulus softening effect was also considered. A practical method was proposed to compute the rolling resistance and transient temperature distributions by establishing a 2-D axisymmetric model. A rubber rolling tester was used to verify the numerical results. The comparison between numerical data and test data reveals that the proposed analytical method is a reliable approach to predict rolling resistance and transient temperature distribution for rubber tires. At last, the dependence of rolling resistance and heat build-up on thermal conductivity and loss factor were investigated by the parametric numerical experiments.

1. Introduction

To improve the fuel efficiency of tires on a variety of vehicles is a great challenge and hot topic in rubber industry. The research and development of high-performance tires with high abrasion resistance, great wet skid resistance and low rolling resistance (RR) are in urgent needs; however, significant heat build-up occurs in tires when subjected to a dynamic excitation because of the nonlinear viscoelasticity of elastomer materials [1–3]. Significant heat generation implies high energy loss and RR of tires, which result in large fuel consumption and carbon emission of various vehicles. Many research work have been done and remarkable progresses have been made towards the target of rubber materials with low loss factor from the points of rubber and filler type [4–7], dispersion [8], curing and crosslinking [9], interfacial modification [10–13], and processing [14,15].

Numerical simulation with the advantage of low cost and short period is often required in the early product development cycle [16–18]. Finite element analysis is an efficient approach to simulate the heat build-up behavior for rubber compound. Clark [19] proposed a model to estimate the time to reach thermal equilibrium. Whicker et al. [20] proposed a thermo-mechanical coupling method to calculate the power loss of tires. Ebbott et al. [21] used the same approach to compute the steady temperature distributions. The fully coupled iterative method was simplified into a non-iterative computing approach

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through a concept of deformation index [22,23]. Gibert et al. [24] simulated the transient temperature distributions of a non-pneumatic tire on the basis of the deformation index concept, but without experimental verification. Mars et al. [25] presented a theory to predict the transient response of RR to changes in velocity from empirical data generated at steady state. Shida et al. [26] proposed a RR analytical approach, and the calculated results of a passenger radial tire accurately captured the trends of an actual tire. Ghosh et al. [27] developed a RR code to compute the energy dissipation rate of tire by using the product of the strain energy density and loss factor of rubber compounds. Cho et al. [28] predicted the temperature distribution and RR of a 3-D periodic patterned tire and gave a satisfactory numerical results. Great progresses on the simulation of steady or transient temperature distribution and RR of rubber tires have been achieved. However, few works focus on each detail in the flowchart of heat build-up and RR analysis simultaneously; for example, the precise acquisition of rubber mechanical and thermal properties, the dependence of the viscoelastic property on the strain, temperature and frequency, and the consideration of creep effect and dynamic properties softening effect, etc.

In our previous work [3], we examined the mechanisms of heat build-up and predicted transient temperature distributions for a cylindrical rubber specimen. Many details in the flowchart of heat build-up analysis were considered simultaneously; that is, the reliable acquisition of rubber material parameters, the dependence of the loss modulus on the strain and temperature, creep effect and Mullins effect on the dynamic property of rubber composites, and the reliable experimental data to verify the numerical data. The purpose of this work is to establish an analytical method to accurately compute the transient temperature distribution and RR of a solid rubber tire.

2. Experimental

2.1. Rubber materials

The rubber material was based on a recipe of 100 phr natural rubber (NR, Ribbed Smoked Sheet 1#), 40 phr carbon black N234 (Tianjin Cabot Chemical Products Co., Ltd.), 3 phr zinc oxide, 1phr stearic acid, 1 phr sulfur, 1 phr accelerant CBS, and 4 phr antioxidant as processing aid. The unit phr means parts per hundred parts of rubber. The optimum cure time t_{90} for rubber sheets with a thickness of 2 mm is 11 min.

2.2. Preparation of the solid rubber tire

The solid rubber tire with a thickness of 20 mm, a width of 18 mm, and an external radius of 51 mm shown in Figs. S1(a) and (b) is composed of two part: metal rim and rubber tire. The metal rim and rubber material were put into the curing mold on a platen presser at 143 °C under 15 MPa. After the vulcanization, we obtained solid rubber tires for the following tests.

2.3. Characterization

2.3.1. Constitutive model

Uniaxial tension, planar tension, and equibiaxial tension with the consideration of Mullins effect were used to determine the constitutive model of rubber material.

2.3.2. Nonlinear viscoelastic model

The dependence of loss modulus on the strain amplitude and temperature were characterized by a brand new advanced DMA + 1000 analyzer manufactured by AREVA 01 dB-Metravib (France) Co., Ltd. The strain amplitude ranged from 0.1% to 100%, the temperature ranged from 35 °C to 115 °C with a step of 10 °C, and the loading frequency was 10 Hz. The dependence of loss modulus on the frequency was also studied. The frequency ranged from 1 Hz to 50 Hz, and the temperature ranged from 20 °C to 80 °C with a step size of 10 °C.

2.3.3. Thermal conductivity test

Thermal conductivity (λ) were measured by a DTC-300 thermal conductivity tester (TA Instruments Waters LLC, USA) over the temperature range 30–140 °C with a step size of 10 °C. To reduce the measurement error, λ was measured three times for each temperature point.

2.3.4. RR and temperature rise test

RR vs. time and temperature vs. time curves were recorded by a rubber rolling test apparatus (RSS II, Beijing Wanhuiyifang Science and Technology Development Co., Ltd.) shown in Fig. S1(c). The rotating speed was set to be 600, 800, 1000, and 1200 *r/min*, respectively. The environmental temperature was 25 °C, and the application time was 120 min.

2.3.5. Other tests

Detailed description of the measurements of the uniaxial tension, planar tension, equibiaxial tension, specific heat capacity, and loss modulus softening behavior for the rubber material can be found in our work [3] and Ref. [34].

3. Numerical implementation of heat generation and RR analysis

3.1. Complexity of heat generation analysis for the solid rubber tire

Energy dissipated per unit volume per cycle (H) is called hysteresis energy density according to the theory of rubber viscoelasticity [13]. When the loading cycle is strain controlled sinusoidal excitation, the formula of H was shown in Eq. (1). In the formula, σ_a is stress amplitude, γ_a is strain amplitude, δ is lag angle between stress and strain, and G'' is shear loss modulus [20].

$$H = \int_0^{2\pi/\omega} \sigma(t)\frac{d\gamma(t)}{dt}dt = \pi\gamma_a^2 G'' \tag{1}$$

But simulating energy dissipation behavior of a solid rubber tire is much more complicated than that of a cylindrical rubber specimen in our previous study [3]. First, the time history of strains during one rotation period exhibits a non-sinusoidal complicated signal, so Fourier sine series shown in Eq. (2) was applied to approximate time history of the strain amplitude. In the formula, θ is the circumferential position ranged from 0 to 2π, $\gamma_{a,k}$ is the Fourier coefficient of the strain, and N is the order of the Fourier series. Then H of the solid tire can be computed according to Eq. (3). T is temperature, and f is frequency. Heat generation rate ($\dot{Q}$), the heat dissipated per unit time per unit volume [30], can be written as shown in Eq. (4).

$$\gamma(\theta) = \sum_{k=1}^{N} \gamma_{a,k} \sin\left(\frac{k}{2}\cdot\theta\right) \tag{2}$$

$$H = \frac{\pi}{2}\cdot\sum_{k=1}^{N} k\cdot G''(\gamma_{a,k}, T, f)\cdot\gamma_{a,k}^2 \tag{3}$$

$$\dot{Q} = H\cdot f \tag{4}$$

Second, 2-D axisymmetric geometric model which can save much computational time cannot be directly used to model the heat generation of the 3-D solid rubber tire because the boundary condition in the static tire-road contact analysis is asymmetric. A practical and efficient method was proposed to calculate the transient temperature distribution and RR of the 3-D solid tire.

In addition, when the solid tire rotates, the temperature increases and the strain amplitude differs for each material point, the relation between loss modulus of rubber composite and temperature, strain, and frequency should be established. Here we used the modified Kraus