ANALYZING RESISTANCE ON PNEUMATIC TIRES USING ENERGY MODEL

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ABSTRACT

During movement, wheels' deformation causes energy dissipation. Viscous resistance of rubber materials in tire's carcass and tire's patterns affect vehicle's rolling resistance. This paper analyzes rolling resistance on interaction surface between tires and road, using energy model based on non-linear Mooney-Rivlin with two parameters of stress and deformation. The research is on 3-D tire model in case of static structure, transient structure and explicit dynamics, using finite element simulation in Ansys Workbench. The results are energy consumption and rolling resistance of 2 types of flat tires in F1 racing cars and tires with longitudinal patterns in cars. From here it is possible to analyze further rolling resistance in other types of tires.

Keywords: *Tyre, Energy model, Rolling resistance.*

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1. INTRODUCTION

Auto wheel consists of rubber tire, rim and disc. Wheel requires fatigue strength, high load capacity and long life [1]. Tire structure id devised into 2 main groups: Carcass and abrasion resistant tread, which are 2 main rubber components, withstand internal and external loads and provide necessary strain force at the tread's edges. Several layers of steel or nylon belts, bead stiffen the tread, strengthen the carcass and prevent excessive deformation of rubber. During movement, there are resistances that affect vehicle kinetic and dynamic characteristics, among which, the resistance at interaction surface between tires and road dissipates 10 - 33% of energy generated from the engine [2, 3]. The main source of rolling resistance is the energy dissipated at the contact surface between tires and road [4, 5]. Energy dissipation is usually studied in designing tires along with customers' experiences. Finite element application FEM on 3-D tire's model is commonly used in designing tires by analyzing deformation cycles in order to determine energy loss at the contact surface between tires and road [6, 7]. Rubber viscoelastic hysteresis causes cyclic deformation, which change tire's rolling resistance in its movement [8, 9]. Numerical method approximates losses, using elastic properties and resistance [3]. One of the solutions to improve accuracy is using Fourier series in calculating and tire's deformation cycles [9]. Experimental measurements show that rolling resistance varies with the complexity of operating conditions [10].

2. MODELING AND SIMULATING

2.1. Energy model

Tire rolling resistance is the ratio of energy loss Φ_w divided by tire's travel distance in 1 revolution in equation (1) [11, 12]. Distribution of energy loss in the biggest tire as followings: 80 - 95% in sidewalls, 15% in contact surface with road, 5% by tire's aerodynamic resistance.

$$P_f = \frac{\Phi_W}{2.\pi.r_L} \tag{1}$$

Where: P_f is rolling resistance, Φ_W is energy loss, r_L is tire's radius.

The loss Φ_W of deformation energy is calculated by Strain Equivalent Von-mises σ in equation (2) [13, 14].

$$\Phi_W = \int_V \int_0^{f_c} \sigma_{ij}(t)\frac{d\varepsilon_{ij}(t)}{dt}dtdV \tag{2}$$

Where: V is tire's volume when fully inflated and loaded, f_c is tire's rotational frequency, σ_{ij} and ε_{ij} are components of local stress and deformation at node i,j.

Based on non-linear Mooney-Rivlin model, local stress and deformation in fully inflated and loaded tire are calculated in equation (3).

$$\sigma_{i,j} = 2\left(\lambda - \frac{1}{\lambda^2}\right)\left(C_{o1} + \frac{C_{10}}{\lambda}\right) \tag{3}$$

Where: $\sigma_{i,j}$ is Equivalent Von-mises Stress; C_{01} (MPa) and C_{10} (MPa) are tire's material constants, λ is Mooney-Rivlin coefficient as determined in equation (4).

$$\lambda = C_{10}\left(d_{f1} - 3\right) + C_{o1}\left(d_{f2} - 3\right) + \frac{1}{D}\left(J_e - 1\right)^2 \tag{4}$$

d_{f1} and d_{f2} are the 1^{st} 2 deviations, J_e is deformation ratio of tire's volume [15]. D is compressive stiffness found in graph of tire's stress and deformation [16].

2.2. Simulation

The analysis uses finite element tool in Ansys Workbench version 2022R1. Simulation modules resolve 3 problems: (1) Static Structural: analyzes model of tire - disc - road surface in order to determine displacements, stress, deformation and internal forces caused by loads, which slowly vary over time. Damping and inertial forces are very small or do not appear and may be ignored. (2) Loads include: external pressure and forces caused by vehicle's weight placed vertically on wheel blocks, and by rotating wheels' torque; inertial forces in steady state (gravity or rotational acceleration); non zero displacement; temperature (appear in rubber components and contact surface between tire and road). Transient Structural: analyzes structures over time history in order to determine dynamic response of structures under load impact. The results are displacements, deformation, stress and changing forces with consideration of anti dumping or inertial effects. (3) Explicit Dynamics: executes simultaneously different dynamic simulations, including: non linear model of metallic, non metallic structures, compressive air in tires, and their interactions.

2.3. Tire's parameters for simulating

For comparison, the study selects tires with similar shapes and rolling surfaces: F1 racing car's tires and Toyota Camry tires. Tires' geometric parameters as followings:

F1 racing tires: 405/670-R13, tire's width 405mm, tire's diameter 670mm, tire's radius 335 mm. Toyota Camry tires: 235/45R18, tire's width 235mm, rim's diameter 18 inch (457mm), tire's diameter 563mm, tire's radius 281mm.

The tire is made of mixed materials, labeled as Rubber, butyl (IIR, 30 - 50% carbon black) including natural rubber, butyl material mixed with black carbon with ratio of 30 - 50%. The rim's disc is made of stainless steel. The road surface layer is of asphalt concrete.

Loads on tires are selected equally in order to compare simulation results. Loads on tires, pressure, equivalent static deviation, temperature, energy dissipation of tire's deformation are related to contact area with road surface.

3. ANALYZING RESULTS

Stress, deformation and deformation energy in tire

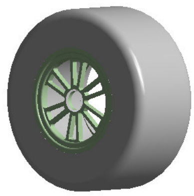
Two types of tire used in simulation shown in Fig. 1. Tire with flat surface is used for F1 racing car with very high speed of over 200km/h as shown in Fig. 1a. Commercial car (small car, bus), with common speed from 60 to less than 200km/h, uses tire with longitudinal patterns along its circumference as shown in Fig. 1b. Differences in patterns lead to differences in heat distribution, elastic coefficients, tire vibration. Thus, tires's slides on road surface are different [18].

The tire slip lenght *s* is approximated equal calculation in equation (5).

$$s = \frac{(V - R_e w)}{V} \quad (5)$$

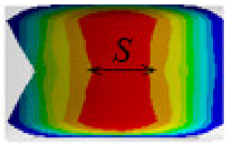
Where: V is the longitudinal speed of the center, Rc is the effective wheel radius, w is the angular wheel's speed.

Calculating time of each module in simulation is 70(s). In the results, images of color spectrums can be viewed directly. Tire's slides show appropriate patterns in Figs. 1c and 1d.

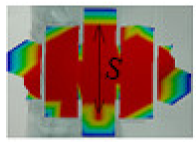


a) Tire of racing car

b) Tire of car



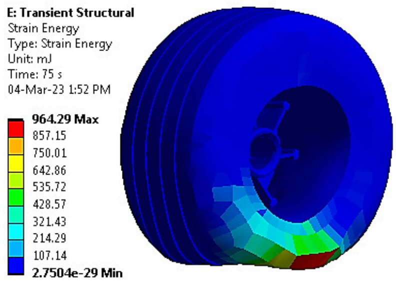
c) Slide of F1 tire



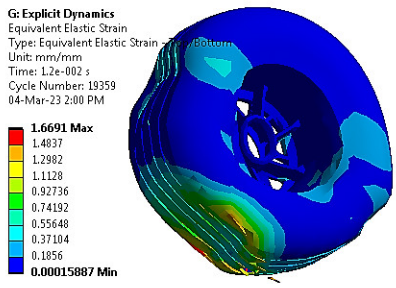
d) Slide of car tire

Fig. 1. Images of tires and slides on road surface

Analyzing Transient Structural module, we get maximum strain energy 964.29MJ in cycle 75 (s) shown in Fig. 2a. Similarly, we get equivalent strain value 1.6691 (mm) in cycle 1.2e-002 (s) in module Explicit Dynamics shown in Fig. 2b.



a) Strain Energy

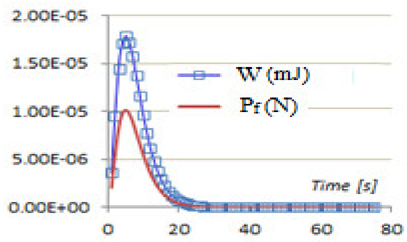


b) Equivalent Elastic Strain

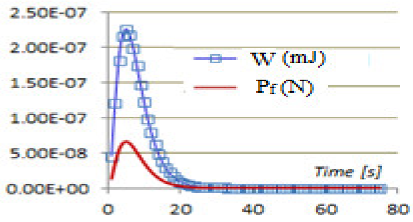
Fig. 2. Strain Energy and Equivalent Elastic Strain of tire

Rolling resistance Pf

In equation (1) above, rolling resistance P_f varies according to strain energy over time period (t). In the results of simulating Transient Structure module, we get strain energy loss over time period from 0 to 70 (s) in accordance with changing load over that time. Strain anergy Φ_W_racing car and rolling resistance P_f_racing car in racing tire are 1.75E-05 (mJ) and 1.00E-05 (N) respectively, while those values in tire of small car are 2.25E-07 (mJ) 5.20E-08 respectivey shown in Fig. 3. These results are due to that racing tire has flat surface, so the sliding area on road surface is bigger than that of patterned tire in car.



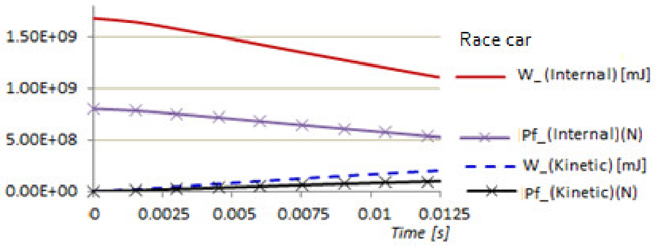
For racing car



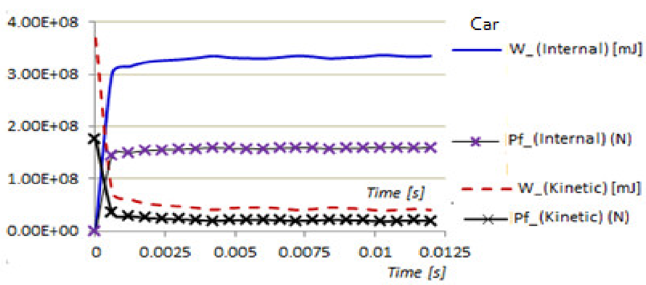
For car

Fig. 3. Results of analyzing rolling resistance and strain energy

Analyzing Explicit Dynamics determines strain energy loss, since the internal forces in tire's carcass Φ_W_(Internal), which mainly causes thermal deformation (heat transfer is not considered here), gradually decreases, and Φ_W_(Kinetic), which is caused by external forces, gradually increases. Corresponding rolling resistance is also related by equation (1) above. The results obtained in period from 0 to 0.0125 (s) with changing loads. The changing strain energy and rolling resistance in racing tire shown in Fig. 4a, and of tire for small car shown in Fig. 4b. Those values in racing tire are bigger than that in tire of small car, since racing tire has flat surface its sliding area on road surface is larger than that of smal car.



a) For racing car



b) For car

Fig. 4. Results of analyzing rolling resistance and strain energy

4. CONCLUSION

In the results, rolling resistance varies in accordance with strain energy loss. Increasing strain leads to increasing rolling resistance.

Using simulation in Ansys Workbench, surveying static state in Static Structure module, and surveying dynamics in Transient Structure and Explicit Dynamics modules determine values and find rules of changes in strain energy loss in 2 tires, which have similar surfaces but different patterns. F1 racing tire with flat surface has larger sliding area than that in tire with grooved patterns in small car.

Quantitative analysis results can be used in tire design with shortened time and improved tire properties.

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