Tire-Pavement System Modelling and Triaxial Contact Stress Analysis

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Abstract. In the pavement design, the tire load is usually assumed to be a circular or rectangular evenly distributed load, which is actually not like this. In order to provide data reference for the development of tire-pavement contact stress intelligent test instrument, it is necessary to model the tire-pavement system, and construct tire-pavement 3D finite element model using large finite element software. Firstly, establish three-dimensional model of tire and road surface, and impose certain loads and constraints. Secondly, the triaxial contact stress of the tire-pavement under static conditions is analyzed. Then the triaxial stress under traction conditions is analyzed, and the triaxial stress under different conditions of use of the tire is compared and analyzed. The results show that as the load of the tire gradually increases, the maximum vertical contact stress and the maximum longitudinal stress gradually decrease, but the maximum lateral pressure gradually increases. When the inflation pressure of the tire is gradually increased, the contact stresses in the three directions are correspondingly increased. However, the maximum vertical contact stress and maximum longitudinal stress increase more obviously than the maximum transverse contact stress. In addition, the transverse contact stress could be ignored under traction conditions.

1. Introduction  
As an important part of the vehicle, the tire carries the load transfer between the vehicle and the pavement. The problem of contact with the road surface seriously affects the driving performance of the car [1]. Under static conditions, there is a triaxial stress distribution between the tire pavements, and under the traction condition, the characteristics of the stress distribution will change to a large extent [2, 3]. Therefore, ABAQUS analysis software was used to establish the finite element model of truck tire and pavement respectively, and the three-dimensional model of tire-road contact was established [4]. This paper analyzes the triaxial stress distribution characteristics of the tire-pavement contact, compares the variation rules of the triaxial stress distribution of the tire under different service conditions, in order to provide a data reference for the development of the tire pavement contact stress intelligent test instrument.

2. Establishment of finite element model  
With the significant increase in the number of vehicles transported by overload, the vehicle load is also increasing, resulting in shortened tire life and road damage, which requires a targeted study of the
load of truck tires. According to the national standard GB/T2977-2016, the 315/70R22.5 general-purpose radial tires for trucks are selected [5].

2.1. Model of the rubber part of the tire
The rubber material is a typical superelastic material that exhibits a distinct nonlinear elastic response, and its stress-strain relationship is described by the strain potential energy [6]. Common strain potential energy functions include polynomial model, Ogden model, Arruda-Boyce model and Van der Waals model, among which polynomial models are the most common, which can be expressed as:

\[ U = \sum_{i=1}^{N} C_{ij} (I_1 - 3)(I_2 - 3) + \sum_{i=1}^{N} \frac{1}{D_i} (J - 1)^{2i} \]  

(1)

Where \( U \) is the strain potential energy, \( N \) is the polynomial order, \( C_{ij} \) is the material parameter, describes the shear characteristics, \( I_1 \) and \( I_2 \) are the distortion metrics of the material, \( J \) is the elastic volume ratio, \( D_i \) is the material parameter, and introduces compressibility. If \( N \) is equal to 1, the initial shear modulus \( \mu_0 \) and the bulk modulus \( K_0 \) of the material are:

\[ \mu_0 = 2(C_{01} + C_{10}) \]  

(2)

\[ K_0 = \frac{2}{D_1} \]  

(3)

Formula (1) could be simplified to:

\[ U = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{D_1} (J - 1)^2 \]  

(4)

Formula (4) is the compressible model applied to the rubber part of the tire of this paper. It can better simulate the material properties of small strain and medium strain, and is closer to the experimental data.

2.2. Model generation
Firstly, a two-dimensional section model of the tire is established. After symmetry and rotation, the generated three-dimensional model of the tire is shown in figure 1. Since the deformation of the tire is much larger than the deformation of the road surface, it can be assumed that the road surface is a rigid road surface [7,8], and a three-dimensional model of the tire contacting the road surface is shown in figure 2.

![Figure 1. 3D model of the tire.](image1)

![Figure 2. The tire-pavement three-dimensional model of contact.](image2)
3. Stress analysis of tire - pavement under static conditions

When the tire comes into contact with the road surface, the tread in the contact patch is compressed and subjected to compressive stress, and the side part of the tire is stretched and subjected to tensile stress, resulting in uneven distribution of normal pressure in the contact patch between the tire and the road surface. In addition, different tire material poisson ratio and special tire pattern structure promote the generation of shear stress [9,10]. This is the main reason for the normal contact stress, transverse stress and longitudinal stress between tire and pavement.

![Figure 3. Tire-pavement contact area nephogram](image)

![Figure 4. Normal stress nephogram](image)

![Figure 5. Transverse stress nephogram](image)

![Figure 6. Longitudinal stress nephogram](image)

In the analysis in this section, besides the pneumatic pressure of $P = 600$ kPa, the vertical load of $F = 8$ kN is applied to the tire, and the friction coefficient between the tire and the road surface is 0.6. After calculation and analysis, figure 3 shows the cloud diagram of contact area between tires and road surface. CNAREA is used in ABAQUS to represent the cloud diagram of contact area. It can be seen that the contact area in the middle red area is the largest, and the farther away it is, the smaller it is. As shown in Figure 4, the normal contact pressure between tires and pavement is not uniformly distributed in the structural design specification of asphalt pavement. In ABAQUS analysis, CPRESS
is used to represent the normal contact stress. The maximum vertical stress is 876.9 kPa, and the positive value indicates that the vertical stress is compressive stress, and the vertical downward value indicates a positive sign. Figure 5 shows the distribution cloud diagram of transverse stress (CSHEAR2) in the tyre-pavement contact. The maximum transverse stress is +126.8kpa and -126.8kpa, respectively. Figure 6 shows the distribution cloud diagram of the longitudinal stress (CSHEAR1) on the tyre-pavement contact. The maximum longitudinal stress is +88.75kPa and -88.75 kPa, respectively. The longitudinal stress values have positive or negative, and the lateral center line of the tire grounding mark is symmetrically distributed.

4. Stress analysis of tire - pavement under traction condition

In the process of full traction, the tire-road contact stress is similar to the normal contact pressure under the static condition, but shear stress changes greatly. Take the linear velocity $V$ of the tire to be 10km/h (i.e., $V=2.778m/s$), and simulate the contact stress of traction condition through different rotational angular velocities of the tire. Figure 7 shows the longitudinal force corresponding to different rotational angular velocities of the tire. When the angular velocity $w$ of the tire rotation is 6 rad/s, the tire is in a fully traction state. Figure 8 shows a cloud diagram of the normal contact stress between tire and pavement. The maximum normal contact pressure is 860.2 kPa, and the size and distribution characteristics are similar to the static state. Figure 9 shows a cloud diagram of the transverse contact stress between tire and pavement. The maximum transverse contact stress is +12.97 kPa. The lateral contact stress is not completely balanced. This is because the tire is in a state of complete traction and the tire is sliding on the ground. However, the lateral contact stress is small and could be neglected. Figure 10 shows tire-pavement cloud diagram of the longitudinal contact stress, the largest longitudinal contact stress of 516.1 kPa, the direction of the longitudinal contact stress are negative, mainly because under the completely traction, the power output of the engine is transmitted to the tires, the ground exerts a forward driving force on the tire, and the ground is subjected to the rearward force of the tire, so the longitudinal contact stress is negative [11].

4.1. Influence of different tire loads on contact triaxial stress

Tire-road contact stress is affected by various factors such as tire load, tire inflation pressure, friction coefficient, road material and road surface unevenness excitation. In the traction condition, the linear speed of the center of the tire is 10km/h, the angular velocity of the tire rotation is $w=6$ rad/s, and the inflation pressure is 600 kPa. Table 1 shows the influence of different loads on the triaxial stress of the tire. When the load of the tire is gradually increased, the maximum vertical contact stress and the maximum longitudinal stress gradually increase, however, the maximum lateral pressure gradually increases. Compare with vertical and longitudinal stresses, regardless of the maximum transverse stress, are always negligible. This is clearly seen from the ratio of the maximum contact stress.

**Figure 7.** Longitudinal force at different angular velocities  
**Figure 8.** Normal stress nephogram
Table 1. Analysis of the influence of different tire loads on triaxial stress.

| Full traction | Load/kN               | Maximum contact stress(kPa) | Maximum stress ratio |
|---------------|-----------------------|----------------------------|----------------------|
|               |                      | Vertical | Transverse | Longitudinal |                            |
|               |                       | 8(12.5% of the standard load) | 860 | 12.97 | 516.1 | 1:0.015:0.600 |
|               | $V=10\text{km/h}$   | 12.5(50% of the standard load) | 835.4 | 16.43 | 501.3 | 1:0.020:0.600 |
|               | $w=6\text{rad/s}$   | 25(the standard load)        | 833.4 | 32.45 | 500   | 1:0.039:0.599 |

4.2. Influence of different inflation pressures of tires on contact triaxial stress

In the traction condition, the linear velocity of the center of the tire is $V=10\text{km/h}$, the angular velocity of the tire rotation is $w=6\text{rad/s}$, and when the load is $F=25\text{kN}$, as shown in table 2, the influence of different inflation pressures on the triaxial stress of the tire is analyzed. When the inflation pressure of the tire gradually increases, the contact stress in three directions increases correspondingly, but the maximum vertical contact stress and the maximum longitudinal stress are more obvious than the maximum lateral contact stress. As can be seen from tables 1 and 2, the lateral pressure value is always negligible regardless of changes in tire inflation pressure and tire load. Moreover, the vertical stress is approximately equal to the longitudinal stress multiplied by the friction coefficient, indicating that the contact area between the tire and the pavement is a sliding working area under the full traction condition.
Table 2. Analysis of the influence of different inflation pressures on triaxial stress.

|                  | Maximum contact stress(kPa) |
|------------------|-----------------------------|
|                  | Full traction               | Tire inflation pressure /kPa | Vertical | Transverse | Longitudinal | Maximum stress ratio |
| V=10km/h         | 753.3                      | 500                          | 32.41    | 451.8      |               | 1:0.043:0.599       |
| w=6rad/s         | 833.4                      | 600                          | 32.45    | 500        |               | 1:0.039:0.600       |
| F=25kN           | 934.9                      | 700                          | 32.72    | 560.9      |               | 1:0.035:0.600       |

5. Conclusion
Under static conditions and full traction conditions, the normal contact stress between the tire and the road surface is similar in magnitude and distribution, but the lateral contact stress and the longitudinal contact stress are very different. Under the full traction condition, the lateral contact stress is basically negligible, and the longitudinal contact stress is much larger than the longitudinal stress in the static state. The effects of different tire inflation pressures and different tire loads on the triaxial stress magnitude and distribution under traction conditions were analyzed and compared. When the load of the tire is gradually increased, the maximum vertical contact stress and the maximum longitudinal stress are gradually decreased, but the maximum lateral pressure is gradually increased. When the inflation pressure of the tire gradually increases, the contact stress in three directions increases correspondingly. However, the maximum vertical contact stress and maximum longitudinal stress increase more obviously than the maximum transverse contact stress.

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References
[1] Miao Yu; Guoxiong Wu; Lingyun Kong and Yu Tang 2017 Appl. Sci. 7 p 1123
[2] Lu Y J and Yang S P 2010 Applied Mathematical Modelling, 34 p 2698
[3] Zhao L and Ziran R L 2012 Tire Science and Technology, 40 p 83
[4] Wang H and Al-Qadi I L 2012 International Journal of Pavement Engineering, 13 p 310
[5] Shang Yongning, Shen Yude and Huang Keke 2016 China National Standardization Administration Committee p 1
[6] Song Yong and Liang Yanlong 2014 Journal of Highway and Transportation 31 p 112
[7] Wang Y S and Wu J 2009 2nd Int. Conf. on Intelligent Computation Technology and Automation, IEEE Computer Society p 566
[8] Anghelache, G and Moisescu, R 2012 Veh. Syst. Dyn 50 p 1747
[9] Hambleton, J. P and Drescher, A 2009 J. Terramechs 46 p 35
[10] Hao Wang; Imad L. Al-Qadi; Silvia Portas; Mauro Coni 2013 Transport. Res. Rec. 8 p 76
[11] Ghoreishy, M.H.R.; Malekzadeh, M.; Rahimi, H 2007 Iran. Polym. J. 16 p 540