Comparative Analysis of Static and Dynamic Performance of Non-Pneumatic Tire with Flexible Spoke Structure

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Based on ABAQUS software, the three-dimensional finite element models of 195 / 50R16 radial tire and three kinds of non-pneumatic tire, i.e. spoke plate, honeycomb and grid type, are established, and the static and dynamic performance of the four tire finite element models are analyzed. The results show that: In the static condition analysis, the ground pressure of the non-pneumatic tire is distributed on both sides of the tread; The stress concentration of non-pneumatic tire mainly occurs in the grounding area near the support spoke; The deformation area of non-pneumatic tire mainly appears in the area of grounding and adjacent to the grounding spoke; In the analysis of tire steady rolling condition,the ground imprint of non-pneumatic tire is similar to bar rectangle, and the ground pressure distribution is relatively uniform. The static and dynamic characteristics of honeycomb non-pneumatic tire are close to that of radial tire. The research work of this paper will provide some reference for the structural design and parameter optimization of non-pneumatic tire.

Keywords: non-pneumatic tire, ground pressure distribution,load-carrying characteristics, dynamic characteristics

Highlights:

- Three numerical models of non-pneumatic tire and pneumatic tire are introduced.
- The radial stiffness, the grounding performance and the stress and deformation of the spokes in the static characteristics of three non-pneumatic and pneumatic tires are analyzed.
- The regulation of axial displacement and the change of ground pressure in the dynamic characteristics of three kinds of non-pneumatic tire and pneumatic tire are compared and analyzed.
- The static and dynamic characteristics of honeycomb non-pneumatic tire are similar to those of pneumatic tire.

1 INTRODUCTION

The non-pneumatic tire abandons the compressed air, which is an important part of the pneumatic tire, instead of the wheel integrated structure. Compared with the pneumatic tire, the non-pneumatic tire has the advantages of maintenance free, explosion-proof, puncture proof and strong bearing capacity, according to the statistics of China's transportation department, the proportion of traffic accidents caused by pneumatic tires is about 50% [1]. Many scholars in the tire industry analyze and study the structure and bearing capacity of flexible structure non-pneumatic tire [2-4]. non-pneumatic tires are safer than pneumatic tires, The most representative is the design of honeycomb structure, the structure of honeycomb materials has been studied for more than 30 years, on the one hand, honeycomb materials are mainly used in military equipment to absorb high energy impact [5-7]. On the other hand, it is used in the structural design of high strength and low density [8].

In 2008, a honeycomb tire without internal pressure was developed by Madison polymer research center, Wisconsin USA [9]. In order to improve the strength and vibration performance of the wheel, the honeycomb hexagon structure is mutually supported based on the bionics principle, the optimal design of the structure can improve the strength of the wheel, avoid the problem of tire burst and damage, and the wheel structure also has the advantages of low noise and low friction heat generation. A design scheme of mechanical elastic safety wheel with non-inflatable structure was put forward in [10-11].

Gawwad et al. [12] studied the interaction between tire and ground, and analyzed the influence of tire camber on tire performance. TONUK and Goldstein [13-15] explored the magnitude of the force and the moment in the tire

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imprint under rolling, steering and braking conditions, as well as the steering stiffness, braking stiffness and return stiffness of the whole tire. P. Baranowski et al. [16] set up a multistage testing procedure of the tire and proved the accuracy of the test results and the finite element results. M. Kucewicz et al. [17] evaluated the effect of mesh on finite element results by studying the mesh sensitivity. P. Baranowski et al. [18] studied the mechanical properties of rubber at different speeds under quasi-static and strong dynamic conditions. Pldaparti et al. [19-21] established a three-dimensional model of pneumatic tire, and explored the mechanical properties of cord-rubber composite and its influence on tire properties through the finite element software. Jaehyung et al. [22-23] explored the grounding characteristics of honeycomb non-pneumatic tire under different vertical loads and different honeycomb structures, and compared with the traditional pneumatic tire under the same working conditions based on ABAQUS software. Kwangwon et al. [24] applied ABAQUS software to study the static grounding characteristics and steady rolling of honeycomb non-pneumatic tire, and discussed the factors affecting its vibration characteristics. Jaehyung et al. [25-26] conducted a parametric study and experimental design of the honeycomb non-pneumatic tire through the finite element analysis, explored the influence of three variables, namely, spoke thickness, spoke angle and shear band thickness, on the rolling resistance of the non-pneumatic tire, and optimized its geometric structure. Song et al. [27] used the finite element method to study the temperature field distribution of tire in rolling state. Nishiyama et al. [28] have developed an algorithm for transforming finite element and discrete element to improve the calculation efficiency.

Based on ABAQUS software, this paper makes static and dynamic analysis of radial tire and three kinds of non-pneumatic tires with different structures, the main research contents are as follows: (1)The tire finite element model is established, including radial pneumatic tire, spoke plate non-pneumatic tire, honeycomb non-pneumatic tire and grid type non-pneumatic tire; (2)Based on ABAQUS / Standard module, the static analysis and comparison of the tire finite element model are carried out, including load-bearing characteristics, grounding imprint, stress and deformation of spoke plate, etc; (3)Based on the ABAQUS / standard module, the dynamic performance of the tire finite element model is compared and analyzed, including the displacement regulation of the tire center point and the distribution of the ground pressure during the rolling process.

2 THE ESTABLISHMENT OF TIRE FINITE ELEMENT MODEL

2.1Pneumatic Tire Reference Model

Numerical analysis is an important part of tire research. By setting different material properties, different model structural parameters and different boundary constraints, we can effectively study various characteristics of tire [29-30]. Based on ABAQUS software, a three-dimensional finite element model of 195 / 50R16 radial tire is established, as shown in the left part of Fig. 1. The material properties of different components of radial pneumatic tire are different, so the pneumatic tire should be divided into different zones to give different material properties to the tread, crown belt layer, belt layer#1, belt layer#2, inside liner, sidewall, bead wire and other parts. In this paper, the method of defining rebar element in rubber matrix element is used to establish the model.

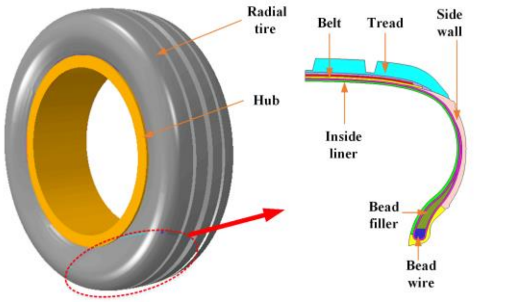


Fig. 1. *3D finite element model of pneumatic tire*

2.1.1Material characteristics of pneumatic Tire

Rubber material is a kind of hyperelastic material, which has approximate volume incompressibility and nonlinearity. In order to better describe the mechanical properties of rubber materials in tire, Neo-Hookean model, the most common molecular statistical constitutive model of rubber materials, is selected in this paper. Table 1 shows the parameters used in the model, this table1 is provided by China triangle tire co., LTD. The strain energy function of Neo-Hookean model describes the compressible rubber material as follows:

$$W=\frac{1}{2}\lambda(\ln J)^2+\frac{1}{2}\mu(I_1-3)-\mu\ln J \qquad (1)$$

The strain energy function of Neo-Hookean model describes the incompressible rubber material as follows:

$$W=C_{10}(I_1-3) \qquad (2)$$

Where: W----Strain energy density; λ ----Elongation ; J----Volume ratio before and after deformation ; μ ----Material stress class constant; $\bar{I}_1$ ----The first invariant of principal elongation ratio; C_{10} ----Material constants.

Table 1. *Rubber material parameters*

Rubber material	C_{10}	D_1	Density（1e-9T/mm^3）
Tread	0.5	0.04	1.11
Sidewall	0.6	0.03	1.12
Inside liner	1.5	0.01	1.10
Apex	6.0	0.003	1.10

The two layers of reinforcement embedded in the tread are made of high-strength steel, the elastic modulus E=2.1×105 MPa and Poisson's ratio v=0.29. The thickness of reinforcement layer is 0.5mm. This steel wire material property is also applicable to the non-pneumatic tire, this material property is no longer described for the non-pneumatic tyre part.

2.2 Structural Parameters and Modeling of Non-Pneumatic Tire

The static analysis and dynamic comparative analysis are carried out for the tire respectively. Therefore, in the modeling stage, the control variables are the same for the general structural parameters of the spoke, honeycomb and grid type non-pneumatic tire. Only the number and structure of spokes as supporting part is different. The unified structural parameters are as follows: The outer diameter is 602mm, the inner diameter is 390mm, the tread thickness is 12mm, and the spoke thickness is 5mm. The three-dimensional finite element models of spoke, honeycomb and grid type non-pneumatic tires are shown in Fig. 2.

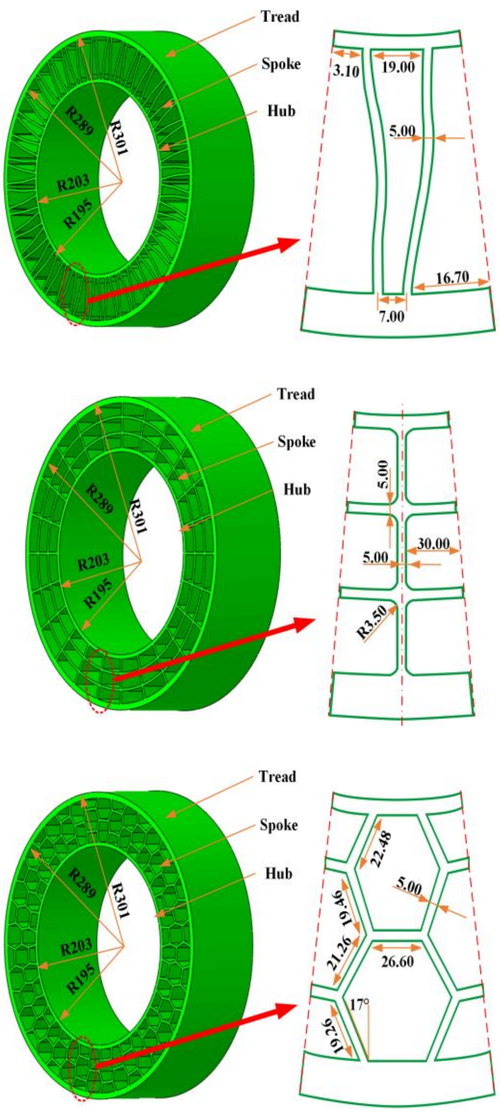


Fig. 2. *3d finite element model of non-pneumatic tire*

2.2.1 Material Characteristics of Non-Pneumatic Tire

The Non-pneumatic tire mainly consists of the following parts: (1) Tread; (2) flexible spokes; (3) two reinforcing layers embedded in the tread. The tread is made of rubber with a thickness of 12mm and is located at the outermost layer of the tire. The relationship between the two reinforcing layers and tread position is shown in Fig.3.

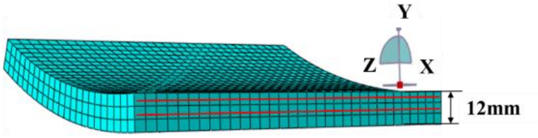


Fig.3. *Two reinforcing layers and tread position relationship*

The tread rubber is dumbbell shaped and the upper and lower ends are fixed on the tensile tester, the stress-strain relationship is obtained by the tensile stress-strain tester(Instrument model:WDW-100), as shown in Fig. 4.

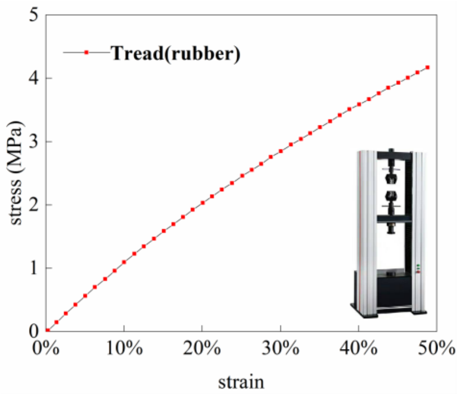


Fig. 4. *Material parameters of tread rubber*

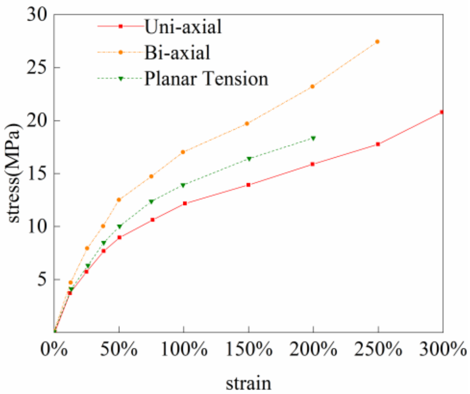


Fig. 5. *Stress and strain relationships of uniaxial, biaxial and planar tension in non-pneumatic tires*

Polyurethane has not only high elasticity of rubber material, but also high strength of plastic material, excellent comprehensive performance, wear-resistant, flame-retardant characteristics, long service life, simple production process, green environmental protection and many other characteristics. It is an ideal material for manufacturing tires. The carcass is made of polyurethane elastic material. According to the literature, the relationship between stress and strain is shown in Fig. 5[31].

2.3 Finite element simulation Settings

Hexahedral element has high accuracy and good convergence, so it is better to use hexahedral element for solid element. Therefore, C3D8R [32] unit is used for ground structures and Non-pneumatic tire structures. Among, SFM3D4 unit is used for the belt and cord layers in the pneumatic tire, and M3D4R unit is used for the reinforcement layer in the non-pneumatic tire. The same part structure of the four tires is divided by the same mesh type and mesh size. The number of elements for non-pneumatic and pneumatic tires is controlled between 100,000 and 120,000, depending on the specific tire structure, and the number of elements for road surface is unified at 8,000. The number of elements and nodes is no longer stated separately. Both static and dynamic analysis were performed using implicit algorithms. The contact properties were set as tangential behavior and normal behavior, and the friction coefficient was set as 0.7 using the friction formula of penalty function.

In order to improve the calculation efficiency, the road surface is uniformly set as a rigid body. Set the ground to be completely fixed, set the road surface as the first contact surface, set the tread as the second contact surface. The axial positions of pneumatic and non-pneumatic tires are the loading points. In order to avoid the repetition and jumble of the picture, the finite element model of inflatable tire is only used to replace the finite element model of other three types of non-pneumatic tires in Fig. 6 to show the simulation scheme of four types of tires. Both tires and rims are tied using the TIE command.

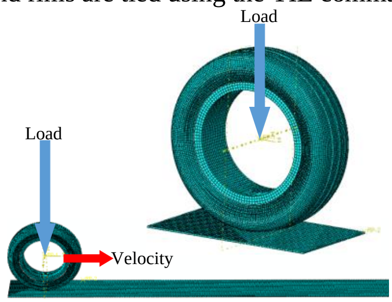


Fig. 6. *Static and dynamic tire finite element simulation scheme*

3 NUMERICAL ANALYSIS OF STATIC PERFORMANCE

In the static analysis, the main research is the deformation of the tire, so the ground and the hub are set as rigid bodies and the ground is completely fixed, in order to reduce the calculation amount and shorten the calculation time. The static analysis of pneumatic tire includes three analysis steps: inflation, contact and loading, while the analysis of non-pneumatic tire only includes two analysis steps: contact and loading. The vertical load of the pneumatic tire and the non-pneumatic tire is 3000N in the loading analysis step, analysis and research on grounding performance of pneumatic and non-pneumatic tyres. The vertical load (500-6000N) was applied to compare the stiffness change trend of non-pneumatic tire and pneumatic tire. Turn on the large deformation switch in all analysis steps.

3.1 Comparison of Static Load-carrying Characteristics of Tire

3.1.1 Radial Stiffness Analysis

When the internal pressure of the pneumatic tire is 240KPa, the comparison diagram of the load-carrying characteristic curve of the pneumatic tire and the non-pneumatic tire with the spoke, honeycomb and grid type formats is shown in Fig. 7, and the reference point is the center point of the tire. In order to fully reflect the authenticity of the numerical analysis. Fig. 8 shows the static load test of pneumatic tire.

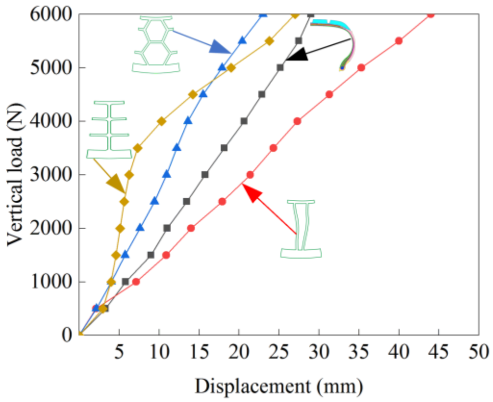


Fig. 7. *Comparison of tire bearing characteristics*

The tire is placed on the loading mechanism to apply different radial loads (Instrument model:CSS-88100), use a laser level instruments ensure excellent level of tires, applied load, get accurate test data. The material properties used for finite element simulation are absolutely consistent with the material properties obtained from the actual tire. The error between the experimental data and the numerical analysis is within 5%, which is enough to reflect the real situation.

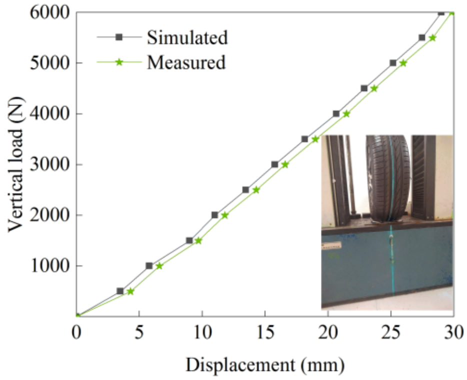
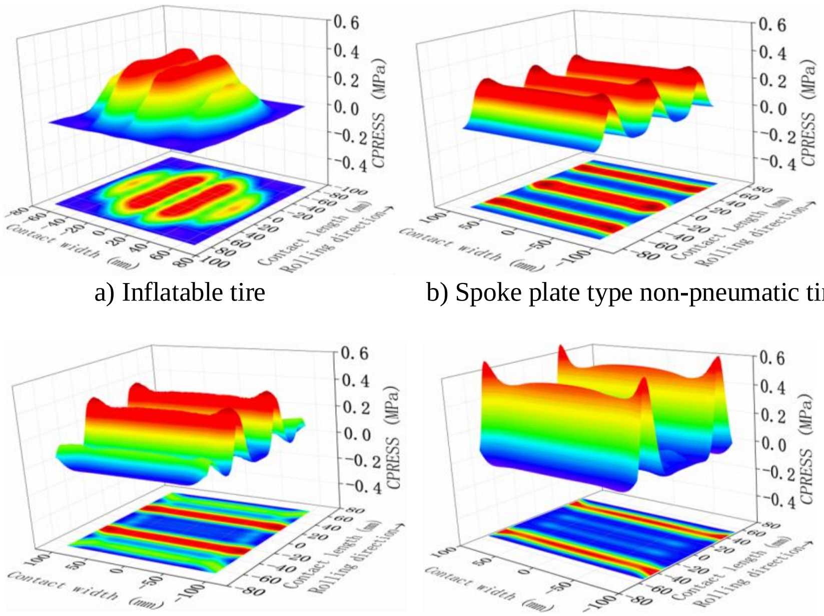


Fig. 8. *Static load test of pneumatic tire*

It can be seen from the comparison diagram of tire load-bearing characteristic curve: (1) The load-carrying characteristic curve of pneumatic tire, spoke plate and honeycomb non-pneumatic tire is approximate to the first-order function, among them, the radial stiffness of honeycomb non-pneumatic tire is the most similar to that of pneumatic tire, while the radial stiffness of spoke non-pneumatic tire is weaker, therefore, the load-carrying characteristics and vehicle driving comfort of honeycomb non-pneumatic tire are similar to those of pneumatic tire; (2) Among the four types of tires, when the radial load is less than 3500N, the radial stiffness of the grid type non-pneumatic tire is the largest, so the bearing capacity is the best, and its radial stiffness is about 4 times of the radial stiffness of the pneumatic tire, when the vertical load is more than 3500N, the radial stiffness of the grid type non-pneumatic tire is similar to that of the spoke Non-pneumatic tire, but the load-carrying capacity of the grid type non-pneumatic tire is much higher than that of the spoke plate non-pneumatic tire.

3.1.2 Analysis of Grounding Performance

Under the action of the rated load of 3000N, the static deformation of the pneumatic tire, spoke plate, honeycomb and grid type non-pneumatic tire is shown in Fig. 9. It can be seen from the figure that the ground pressure distribution of pneumatic tire is similar to the ellipse, and the ground pressure concentration phenomenon appears at the groove position of the ellipse central pattern, and the ground pressure distribution presents a large to small distribution from the ellipse center to the surrounding; The distribution of the ground pressure of the non-pneumatic tire in the form of spoke, honeycomb and grid type is similar to the bar rectangle. From the 3D mapping surface, it can be seen that the t-



a) Inflatable tire b) Spoke plate type non-pneumatic tire

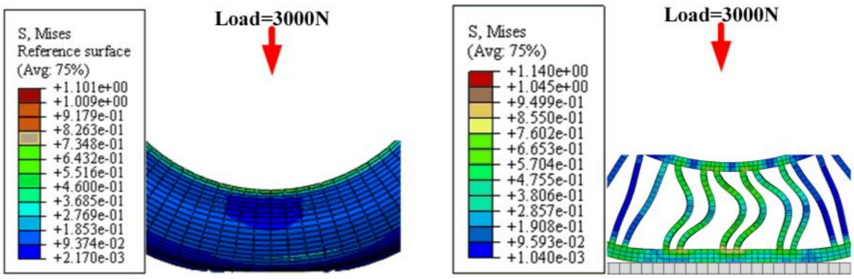
c) Honeycomb non-pneumatic tire d) Grid type non-pneumatic tire

Fig. 9. *Static deformation and grounding mark of pneumatic tire, spoke plate, honeycomb and grid type non-pneumatic tire under rated load of 3000N*

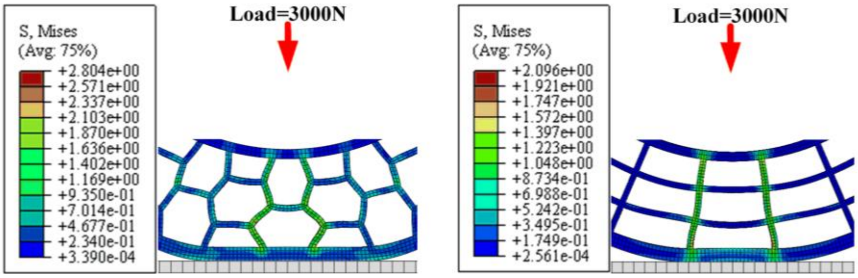
wo sides are not closed, and the ground pressure of the non-pneumatic tire is concentrated at both sides of the connection between the flexible spoke and the tread. The transverse length of the ground pressure distribution of the spoke, honeycomb and grid type non-pneumatic tire is larger than that of the pneumatic tire, while the longitudinal width of the ground pressure distribution is smaller than that of the pneumatic tire, which improves the axial stability of the vehicle.

3.1.3 Stress and Deformation of Spoke

The stress and deformation nephogram of pneumatic tire, spoke plate, honeycomb and grid type non-pneumatic tire under the rated load of 3000N is shown in Fig. 10, the high stress of pneumatic tire is mainly concentrated in the grou-



a) Inflatable tire b)Spoke plate type non-pneumatic tire



c) Spoke plate type non-pneumatic tire d) Grid type non-pneumatic tire

Fig. 10. *Stress and deformation nephogram of pneumatic tire, spoke plate, honeycomb and grid type non-pneumatic tire under rated load of 3000N*

nd tread and sidewall area, while the high stress of non-pneumatic tire is mainly concentrated in the spoke plate and tread belt layer. The stress peak value of the spoke non-pneumatic tire is 0.41 and 0.54 times of that of the honeycomb and grid type non-pneumatic tire respectively, and the stress distribution of the spoke non-pneumatic tire is more uniform than that of the honeycomb and grid type non-pneumatic tire. Where the stress concentration is high, the strain energy density is high, which leads to the decrease of tire fatigue life.

4 DYNAMIC FINNITE ELEMENT ANALYSIS OF TIRE

Using ABAQUS software to establish the tire steady-state rolling finite element model, this paper mainly explores the pressure change and pressure distribution of the tire ground part and the displacement regulation of the tire center point when the tire rolls freely under the condition of the rated load of 3000N and the angular speed of 31.4rad/s. The finite element model is modeled in a unified coordinate system. In the inflation analysis step, fix the central point of the pneumatic tire and apply 0.24MPa pressure on the inner surface of the tire to simulate the inflation condition. Grid division is the same as the type of grid division in static analysis, and it will not be described in detail.

4.1 Displacement Regulation of Tire Center Point

The displacement regulation of tire center point is of great significance to vehicle driving comfort and vehicle structural stability. Fig. 11 shows the change rule of the displacement of the central point of the pneumatic tire and the non-pneumatic tire with time.

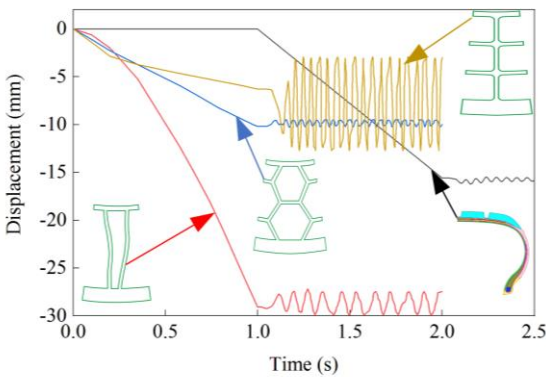


Fig. 11. *Center point displacement curve of tire*

(1) The displacement curve of the central point of the pneumatic tire is under the inflation condition in the period of 0-1.0s, the tire center point is fixed;1.0-2.0s is the loading step, and the tire center point moves down;2.0-2.25s is the acceleration step, and the angular velocity at the tire center point increases from 0 to 31.4rad/s; The period of 2.25-2.5s is steady rolling condition.
(2) The displacement curve of the center point of the Non-pneumatic tire in the period of 0-1.0s is the loading step, and the center point of the tire moves down; The period of 1.0-1.2s is the acceleration step, the tire angular velocity increases from 0 to 31.4rad/s, and the displacement curve fluctuates; The period of 1.2-2.0s is steady rolling stage, and the vertical displacement of tire center point changes periodically.

Under the condition of pure rolling, the angular acceleration (ω) of the tire is 0, and the tangent speed (v) of the center of the tread is the forward driving speed (v_0) of the vehicle, the equation is as follows:

$$v = r_e \omega_0 = v_0 \quad (3)$$

Fig. 12 shows the three radius of the tire. Vertical load has direct influence on effective rolling radius and load radius. researcher [33] proposed a more comprehensive interpretation of the effective rolling radius of the tire.

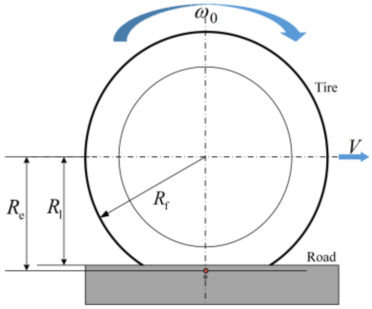


Fig. 12. *The rolling radius of the tire*

Where: r_e --- effective rolling radius; R_l ---radius of tire under load; R_f ---radius of tire under no load; ω_0 --- pure rolling angular velocity.

Both pneumatic tire and non-pneumatic tire are deformable bodies with hysteresis, under the influence of inertia force and centrifugal force in the rolling process, the radius of each particle relative to the tire axis is different, so the tire presents the curve characteristics of wave shape in the rolling process.

It can be seen from the comparison of the displacement regulation of the center point of the non-pneumatic tire and the pneumatic tire in Fig. 9 that the fluctuation amplitude of honeycomb non-pneumatic tire is the closest to that of pneumatic tire. Among them, honeycomb non-pneumatic tire is most similar to pneumatic tire in driving comfort and structural stability during steady rolling; Under the action of 3000N radial load, the radial sinkage of the spoke type non-pneumatic tire is too large, and its driving comfort and vehicle structure stability in the steady rolling process are worse than those of the pneumatic tire, so it is not suitable for the vehicle with larger curb weight; In the steady-state driving process under the action of 3000N radial load, the amplitude of the grid type non-pneumatic tire changes too much, but the sinking of the grid type non-pneumatic tire is the smallest compared with the pneumatic tire, the spoke non-pneumatic tire and the honeycomb non-pneumatic tire, therefore, it can be concluded that the structure of the grid type non-pneumatic tire needs to be optimized, the number of non-pneumatic tire units needs to be increased, and the amplitude of the non-pneumatic tire can be reduced. If want to increase the vehicle's driving comfort and tire grip by increasing the sinking of grid type non-pneumatic tire, we need to improve the material stiffness.

5 CONCLUSIONS

Based on ABAQUS software, 3D finite element models of 195/50R16 radial pneumatic tire, spoke plate type non-pneumatic tire, honeycomb non-pneumatic tire and grid type non-pneumatic tire are established, and their static and dynamic analysis are carried out respectively.

1. Under the action of the rated load of 3000N, the grounding area of the pneumatic tire has axisymmetric deformation, and the deformation area is mainly distributed in the grounding part and sidewall; Because the rubber material of the sidewall of radial pneumatic tire is thin, it is consistent with the actual situation.
2. The deformation area of non-pneumatic tire is mainly distributed in the grounding part and the spokes near the grounding part. The grounding imprint of the non- pneumatic tire is similar to the bar shape rectangle, and the grounding part near the spoke plate has the phenomenon of ground pressure concentration; When the radial load is less than 3500N, the load-carrying capacity of the grid type non-pneumatic tire is the best; When the radial load is more than 3500N, the load capacity of honeycomb non-pneumatic tire is the best. When the polyurethane support structure of the non-pneumatic tire uses the same material model, the radial stiffness of the spoke plate non-pneumatic tire is too small, which is not suitable for vehicles with too large curb weight; However, the radial stiffness of the grid type non-pneumatic tire is too large, which is suitable for vehicles with too large curb weight; The load-carrying characteristics of honeycomb

non-pneumatic tire and radial pneumatic tire are similar.

3. When the tire is rolling, the displacement curve of the tire center point fluctuates during acceleration, and the vertical displacement of the tire center point changes periodically during steady rolling; The overall performance of grid type non-pneumatic tire is not ideal, so its structure needs to be further optimized.
4. In the analysis of tires dynamic characteristics, the amplitude of tires axis position not only has an inevitable relationship with the structure of tires itself, but also has a direct correlation with the vertical load, so it is necessary to reasonably choose the style and type of inflatable tire and non-pneumatic tires according to the requirements of ride comfort and vertical load conditions.

6 ACKNOWLEDGEMENTS

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