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Study on static stiffness characteristics and influencing factors of radial pneumatic tire with complex tread patterns by computer simulation method

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Abstract. **To study the static stiffness characteristics of radial pneumatic tire with complex tread patterns, a numerical simulation model of radial pneumatic tire is established based on the finite element method (FEM), and its accuracy is verified by the outer contour experiment and grounding experiment. The influence of different inflation pressure and cord angle on the radial stiffness of the tire, and the response of the lateral stiffness and longitudinal stiffness of the tire when the pressure and load change are analyzed. The results show that the relationship between tire pressure and radial stiffness is approximately cubic polynomial, and the increase of tire radial stiffness at high pressure is greater than that at low pressure. The increase of air pressure will increase the lateral stiffness of the tire, but the increase is not large. Before the relative slip between the tire and the road surface, the load has little effect on the lateral stiffness and longitudinal stiffness. The research results provide a basis for the structural design of radial tire.**

Keywords-Radial pneumatic tire, Static stiffness, FEM, Influencing factors

I. Introduction

Static stiffness is an important safety performance index of tires, which directly affects the wear resistance of tires, braking and traction, as well as the operational stability, driving safety and comfort of vehicles. The study of tire stiffness characteristics will contribute to the overall improvement of tire structure and performance level.[1]

Hu et al. studied the effect of different types of tread patterns on the rolling resistance of tires based on experimental methods.[2] Zhao et al. investigated the static stiffness characteristics of a non-pneumatic tire by using the combination of finite element and experiment, and analyzed the influence of different structural characteristics on the static stiffness.[3] Zhang et al. studied the radial stiffness of heavy truck tires under static and dynamic conditions, and established a nonlinear model of tire radial stiffness for the study of tire mechanical properties.[4]

A 205/55R16 DS tread radial tire was selected as the research object in this paper. The tire tread pattern was modeled with high precision, and the radial stiffness, lateral stiffness and longitudinal stiffness characteristics of the tire and the influencing factors were simulated and analyzed. The research results provide a basis for tire structure design and vehicle matching.

II. Establishment of 3D finite element model of tire

According to the tire material distribution map, the 2D inner and outer contour of the tire and the material interlayer division line were imported into ABAQUS respectively, and the 2D carcass model was obtained by meshing the model, creating the element set and specifying the element type. In the process of tire simulation, based on the principle of obtaining accurate calculation results with the least calculation cost, it is necessary to simplify the distribution of tire materials appropriately. First, geometric details such as sidewall anti chafing line and marking line were ignored. Secondly, due to the differences in the mechanical properties of the materials of various parts of the tire, the edging film was merged and simplified according to the nearby materials to prevent the overall grid quality from being affected by the thin film material. In addition, the steel wires and fibers in the ply were regarded as stiffeners.

The four node, reduced integral solid element CGAX4R was selected as the tire section element type, and the double node, axisymmetric surface element SFMGAX1 was selected as the skeleton material element type. In ABAQUS, with the help of the axisymmetric model generation command, the 2D carcass model was rotated around a coordinate axis to generate a three-dimensional model, generating contour streamline, so as to define the trajectory of materials in grid transmission for subsequent dynamic analysis. Figure 1 is the 3D carcass model of 205/55R16 tire established by the axisymmetric model generation command. The rubber material was simulated by Yeoh constitutive model,[5] and the specific component parameters are shown in Table 1.

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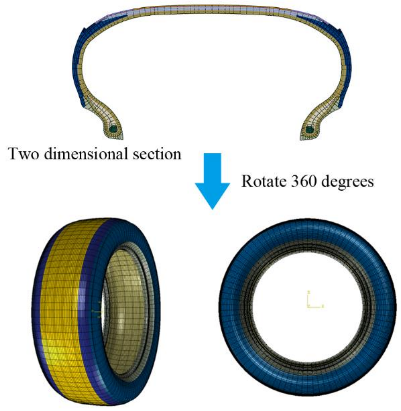

Figure 1. Finite element model of 205/55R16 tire carcass.

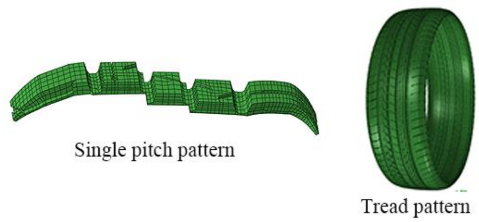

Figure 2. Tire tread pattern model.

Table 1. Rubber parameters selected for different parts of tire.

Part	C_{10}	C_{20}	C_{30}	Compressibility
Tread	7.331E-01	-2.939E-02	2.840E-03	8.264E-02
Tread base	7.408E-01	8.522E-03	1.857E-03	9.038E-02
Belt	1.012E+00	3.899E-02	3.590E-04	4.582E-02
Carcass	1.142E+00	2.660E-02	8.713E-04	6.047E-02
Sidewall	5.279E-01	-2.698E-02	1.027E-03	6.007E-02

As shown in Figure 2, the method of circumferential conformal mapping was used to establish the complex tire tread pattern model, which can effectively avoid using software's own pattern mesh stretching method, and can obtain high-quality tread solid mesh. After the mapped pattern unfolding section was obtained, the outer surface of the tread body became a plane, which can easily depict the tortuous and complex pattern shape. After modeling the main part of the tire and the tread pattern respectively, the combined model technology was used to bind them together, and finally the finite element model of the tire with complex tread pattern was obtained. The finite element model established by the combination of the above methods includes 167960 elements and 222360 nodes.

III. Verification of tire finite element model

A. Tire contour test

The outer contour scanning equipment was used to scan the outer contour of a 205/55R16 tire, as shown in Figure 3, and the outer contour data under no pressure and standard pressure were obtained. The standard inflation pressure of the tire is 250 kPa and the standard load is 6150 N.

Figure 4 shows the comparison of inflation profile simulation and test results. The scanning test profile under 250 kPa pressure is red line, and the modeling profile under 0 kPa pressure is blue line. It can be seen that the simulation analysis inflation contour basically coincides with the scanning test contour, and there is only a small deviation at the left shoulder, about 0.4mm. Therefore, it can be determined that the tire material modeling and pre-processing modeling process have little impact on the tire inflation profile, and can reflect the changes of the actual tire dimensions.

Figure 3. Tire outer contour scanning test.

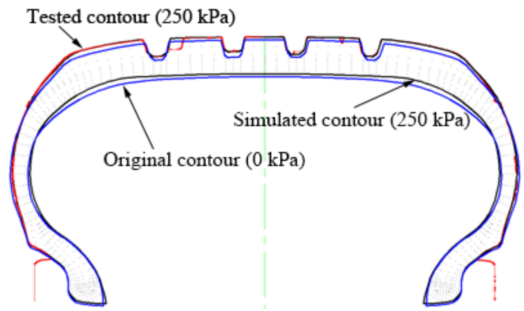

Figure 4. Comparison of simulation and test results of inflation profile.

B. Grounding characteristic test

Figure 5 shows the comparison of simulation and test results of tire grounding pressure distribution under condition 1 (210kpa, 4920 N) and condition 2 (250 kPa, 6150 N). Table 2 is the comparison of grounding imprint parameters under the two working conditions. It can be seen that the ground mark and pressure distribution of the simulation and test results are basically the same, and the established simulation model has small error and good reliability, which can be used to further analyse other tire performance.

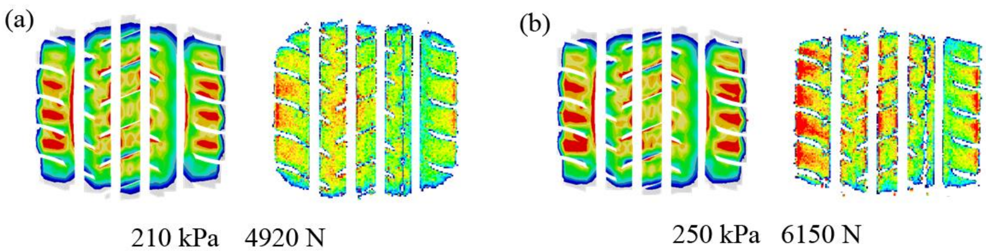

Figure 5. Comparison between simulation and experimental results of grounding pressure distribution.

Table 2. Simulation and test data of grounding characteristic parameters.

Parameter	Condition 1 (210 kPa, 4920N)			Condition 2 (250 kPa, 6150 N)		
	Simulated	Tested	error	Simulated	Tested	error
Impression area /cm^2	213.92	215.97	+2.05	237.5	232	+5.5
Long axis of imprint /mm	147.46	150.88	-3.42	154.3	157.33	+3.03
Minor axis of imprint /mm	160.5	157.7	+2.8	163.3	160.5	+1.4
Deflection /mm	24.3	23.4	+0.9	26.3	25.6	+0.7
Average contact pressure /kPa	305.13	295.56	+9.57	303	307.4	-0.44

IV. Radial stiffness characteristics

A. Influence of inflation pressure on radial stiffness

When the radial stiffness was simulated and analyzed, an upward displacement value of the road control node was set to simulate the settlement of the tire under vertical load. Figure 6 shows the relationship curve between radial load change and tire sinking under working condition I. Comparing the simulation and test data in the figure, the test and simulation results are basically consistent, with an error of 3.4%. In addition, it can be seen that the loading deformation of the tire is basically consistent with the actual tire deformation. During the loading process, the load is roughly linear with the tire deflection, and the deflection increases with the increase of the vertical load. The radial stiffness of the tire increases slightly with the increase of the deflection, which is mainly due to the increase of the internal pressure of the tire.

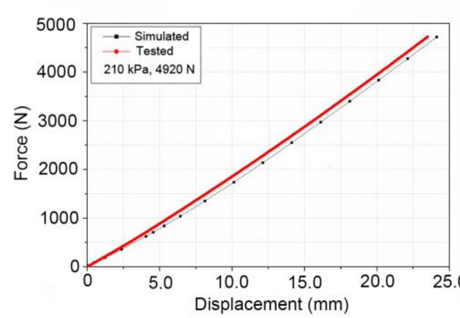

Figure 6. Relationship between the radial load and sinkage.

Figure 7 shows the relationship curves between the tire sinkage and the vertical load when the tire inflation pressure is in the range of 210 kPa to 275 kPa. It can be seen that with the gradual increase of the pressure, the sinkage corresponding to the same load gradually decreases. Figure 8 displays the variation of the tire radial stiffness value and its fitting curve corresponding to different tire inflation pressures. It can be seen that the pressure and radial stiffness of the tire have an approximate cubic polynomial relationship. The increase of radial stiffness value of tire at high pressure is greater than that at low pressure.

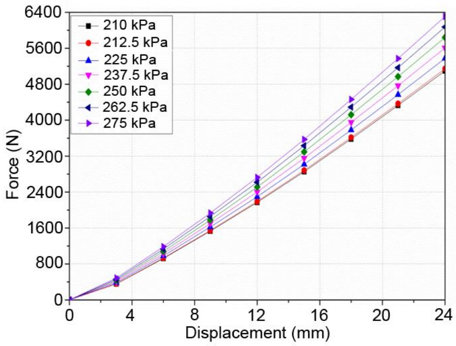

Figure 7. Variation of tire sinkage with load under different pressure conditions.

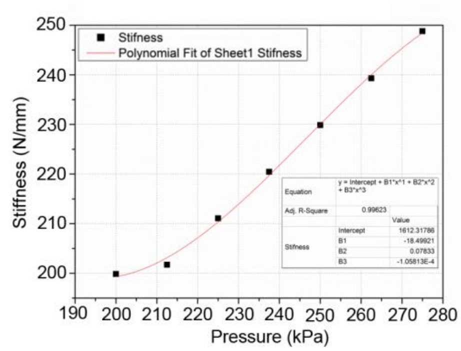

Figure 8. Radial stiffness of the tire at different pressures.

B. Influence of cord angle of belt on radial stiffness

The belt layer has a great impact on the service performance of the tire, and plays an important role in preventing the crown from stretching too much, ensuring the smooth driving of the tire and good contact with the road. Figure 9 shows the relationship between the vertical load and the sinkage within the range of belt angle from 21 ° to 31 °, respectively. Figure 10 shows the variation trend of radial stiffness values corresponding to different belt angles. It can be seen that the change of the belt angle has little effect on the radial stiffness and has a linear relationship, which is mainly because the belt is under pressure during the loading process.

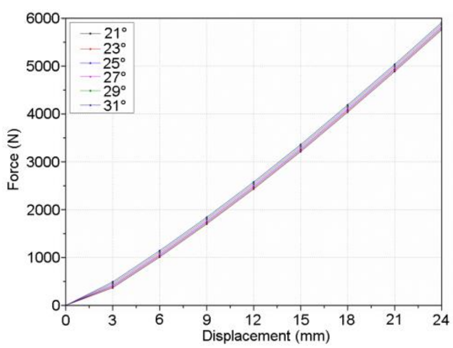

Figure 9. Relationship between load and subsidence under different belt angles

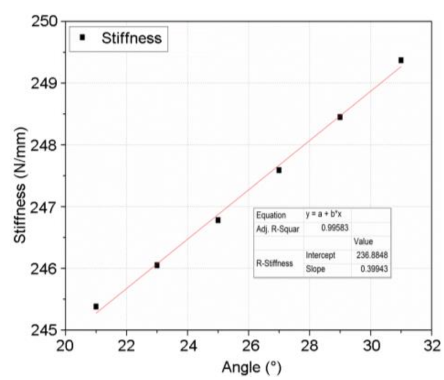

Figure 10. Relationship between belt angle and radial stiffness

V. Lateral stiffness characteristics

A. Influence of inflation pressure on lateral stiffness

Lateral stiffness is one of the main factors that affect the dynamic characteristics of vehicle response in the driving direction. Figure 11 shows the comparison between the simulation and experimental data of tire lateral force and lateral displacement under standard inflation pressure and different load. It can be seen that the simulation analysis is in good agreement with the experimental data, and the error is small.

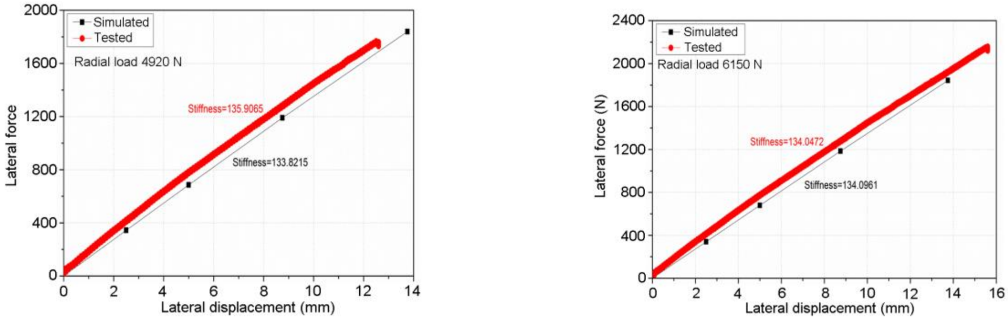

Figure 11. Simulation and experimental data of the relationship between lateral force and lateral displacement under different loads

Figure 12 shows the curves between tire lateral force and lateral displacement under different inflation pressures when standard load is applied. It can be seen that within a certain range, the tire lateral force and lateral displacement increase linearly, but with the further increase of lateral displacement, the growth trend of lateral force slows down until it is stable. Under different inflation pressure conditions, the maximum value of the lateral force is the same, because when the adhesion limit between the tire and the road is reached, there will be slippage. In addition, with the increase of air pressure, the lateral stiffness of the tire will increase slightly. The increase of tire pressure improves the stiffness of the tire, especially strengthens the normal force of the pattern block grounding in the middle of the crown, and enhances the interaction between the tire and the road surface, but the adhesion limit of the rubber and the ground will not change due to the increase of the contact force of the pattern block.

B. Influence of load variation on lateral stiffness

Figure 13 shows the relationship between the lateral force and lateral displacement of the tire under different load conditions at standard pressure. It can be seen that under different loads, the tire lateral force increases rapidly at first, and then the growth trend slows down until it is stable. The lateral adhesion of the tire to the road surface is different under different loads, which reflects that the increase of the normal force can enhance the adhesion limit of the lateral force, but when the load exceeds standard load, the increase range of the lateral force will decrease.

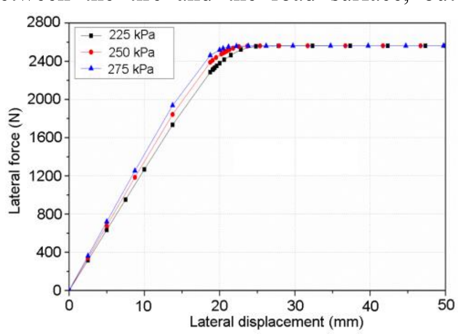

Figure 12. Comparison curve of lateral stiffness under different inflation pressures.

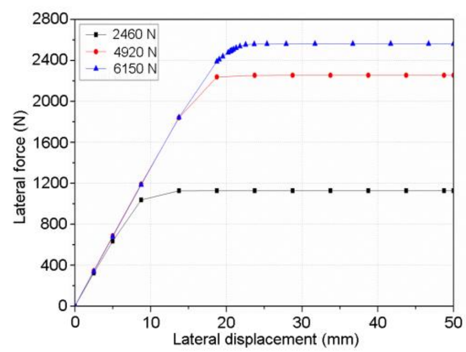

Figure 13. Comparison curve of lateral stiffness under different loads.

VI. Longitudinal stiffness characteristics

A. Influence of inflation pressure on longitudinal stiffness

The longitudinal stiffness of tire is of great significance to the study of longitudinal vibration, traction and braking force of tire. Figure 14 shows the simulation and experimental data comparison of the relationship between longitudinal force and longitudinal displacement under standard pressure and load conditions. It can be seen that the error is 7.6%, which is in line with the actual application accuracy, and in practice, the corresponding scale factor will be modified according to the different loads to achieve higher accuracy.

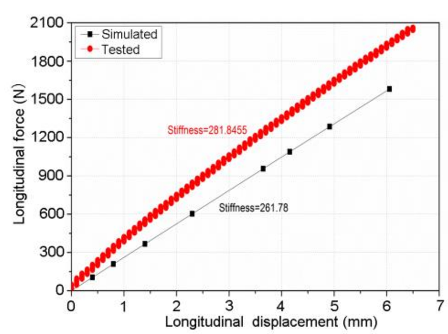

Figure 14. Relationship between longitudinal force and longitudinal displacement under standard load and air pressure

Under the action of standard load, the relationship between tire lateral force and lateral displacement under different inflation pressures is shown in Figure 15. It can be seen that the lateral force and lateral displacement of the tire are basically linear, and the increase of inflation pressure leads to a slight increase in the longitudinal stiffness of the tire. With the increase of tire inflation pressure, the overall rigidity of the tire is improved, the contact effect of the pattern block with the same area on the ground is strengthened, and the force value of longitudinal pumping the ground will also increase.

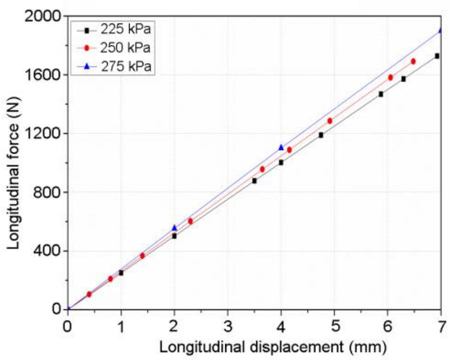

Figure15. Influence of inflation pressure on longitudinal stiffness

VII. Conclusions

The static stiffness of the tire has an important influence on the handling stability, ride comfort and driving performance of the vehicle. In this paper, the finite element model of the tire with complex tread pattern is established, and the characteristics of its radial stiffness, lateral stiffness and longitudinal stiffness were analyzed through the combination of experiment and simulation. The radial stiffness of tire increases with the increase of inflation pressure, and the belt angle has little effect on the radial stiffness. The increase of air pressure will slightly increase the lateral stiffness and longitudinal stiffness of the tire, and the increase of the vertical load enhances the maximum adhesion between the tire and the road surface, but has little effect on the lateral and longitudinal stiffness.

Acknowledgments

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References

[1] Li XY, Xu N, Qiu T, et al. (2020) Influence of anisotropic stiffness on tire mechanical properties and vehicle handling characteristics under combined slip situations. Journal of Jilin University (Engineering and Technology Edition), 50(2): 389-398.

[2] Hu DB, Wang JB, Li L. (2022) Study on correlation between tire rolling resistance and pattern characteristics. Tire Industry, 42: 272-276. (in Chinese)

[3] Zhao YQ, Du XB, Lin F, et al. (2018) Static stiffness characteristics of a new non-pneumatic tire with different hinge structure and distribution. Journal of Mechanical Science and Technology, 32(7): 3057-3064.

B. Influence of load variation on lateral stiffness

Figure 16 shows the relationship curve between the longitudinal force and the longitudinal displacement of the tire when the load changes under the standard pressure. It can be seen from the figure that under standard inflation pressure, the change of the load has little effect on the longitudinal stiffness, reflecting that the longitudinal force and dynamic friction are basically the same when the tire contacts the road and slides relatively at low speed.

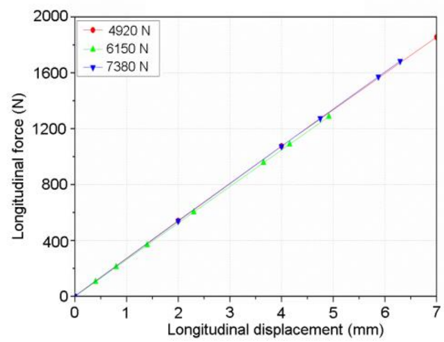

Figure 16. Influence of load on longitudinal stiffness

[4] Zhang Z, Li SH, Zhou JW. (2018) Experimental study on radial stiffness of heavy vehicle tire. Journal of Shijiazhuang Tiedao University (Natural Science Edition), 31(2): 35-39.

[5] Du XB, Zhao YQ, Lin F, et al. (2017) Parameters determination of Mooney-Rivlin model for rubber material of mechanical elastic wheel. Applied Mechanics and Materials, 872: 198-203.