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Study on the Influence of Crown Arc Structure on Tire Grounding Performance

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***Abstract* – Taking 205 / 55R16 radial tire as the research object, the model was established by using Hypermesh and ABAQUS finite element analysis software, and the correctness of the model was verified by the ground pressure test. The tire crown arc was designed with arc width b, arc height h and bionic structure to explore the influence of the tire crown arc on the tire grounding performance. The results show that with the increase of the tire crown arc width, the tire grip and wear performance are improved, and the ground mark is improved; With the increase of the crown arc height, the tire grip and wear performance decreased. The bionic tire crown arc structure design can cooperate to improve the grip and wear performance to a certain extent. The effect of the crown arc structure on the shoulder durability is small, about 3%.**

***Keywords* – Crown Arc Structure, Grip Performance, Wear Performance, Durability, FEM.**

I. INTRODUCTION

As a part of the wheeled vehicle that directly contacts with the ground, the performance of the tire has an important impact on the stability, safety, comfort and economy of the vehicle. In the actual use, the tire crown is the part of the tire that contacts the ground, and the tire crown arc design will have an important effect on the tire grounding performance. Guolin Wang et al. [1] studied the deformation characteristics of different grounding areas by changing the elastic modulus of tread rubber and Poisson's ratio, and explained the influence of the deformation in the grounding area on the ground grip performance. Yukio Nakajima et al. [2] found that excessive grooves increase the deformation of patterns, which further affects the ground grasping performance. Y. Tanaka et al. [3] explored the influence on wear performance by changing the connection mode of crown arc. Cho J.R. et al. [4] used numerical analysis method of wear model to optimize tread pattern and improve wear performance of tires. Shanfeng Hu et al. [5] simulated the stress and strain characteristics of the tire crown under the static load condition and concluded that the end of the tire shoulder band layer was the place prone to fatigue failure. Chunming Xiong et al. [6] selected appropriate fatigue failure evaluation indexes according to different working conditions, and improved tire fatigue life by changing the tire body cord layer height. In summary, domestic and foreign scholars have carried out more studies on tire grounding performance and achieved many important results. Most of them focus on the study of single objective quantity in the grounding characteristic, and few studies on the comprehensive grounding performance.

In this study, a 205/55R16 passenger car radial tire model was established, and the tire crown arc structure was controlled by changing the width b and height h of the tire crown arc, and the bionic tire crown arc design was carried out on the sample tire. Hypermesh and ABAQUS software were used to study the influence of the tire crown arc structure on the ground holding performance, wear performance and durability of the tire, in order to provide a theoretical basis for the tire crown structure optimization and the improvement of the tire comprehensive grounding performance.

II. ESTABLISHMENT AND VERIFICATION OF TIRE MODEL

Before modeling, considering the computational efficiency and simulation convergence of the model, the model is reasonably simplified as follows:

(1) Ignoring the transverse pattern, only considering the longitudinal groove pattern;

(2) The rim and the ground are regarded as rigid bodies, leaving out the rim and its corresponding structure [7].

A. *Finite Element Model*

Due to the complexity of tire structure and the non-linearity of rubber materials, each component is characterized by different materials [8]. The body and the belt layer are rubber-cord composite materials, which are simulated by the Rebar material model. The properties of the Rebar material model are shown in Table 1. Yeoh material model was used to simulate rubber materials such as tread and body, and the constitutive equation of strain energy of Yeoh model was as follows [9]:

$$W = C_{10}\left(I_1 - 3\right) + C_{20}\left(I_1 - 3\right)^2 + C_{30}\left(I_1 - 3\right)^3 \tag{1}$$

Where W is the strain energy; C_{10}, C_{20} and C_{30} are the expansion coefficients of the third-order reduced polynomial; I_1 is the first invariant of strain.

Table 1. Reinforcement material properties.

Rebar Material	**Young's Modulus (GPa)**	**Poisson's ratio (μ)**	**Density (kg/m³)**	**Cord Angle (°)**
Belt steel wire 1	105.9	0.29	7800	66
Belt steel wire 2	105.9	0.29	7800	114
Carcass cords	5.25	0.3	1350	0

B. *Model Validation*

In order to verify the accuracy and applicability of the tire finite element model, the CSS-88100 static loading test machine was used to carry out loading tests on the tire, and the load and grounding mark size were measured. The tire inflation pressure was 2.6 bar and the load was 4000 N. Comparison of test and simulation results of load-subsidence curve under static loading is shown in Fig. 2. The relationship between load and subsidence is approximately linear, and the error between test and simulation is within a small range.

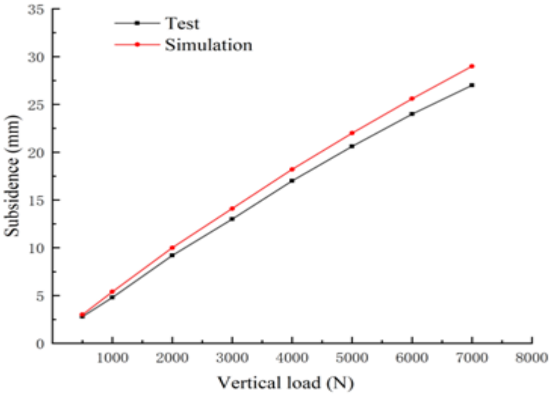

Fig. 7. Load - subsidence curve.

The shape comparison of ground mark of tire under static load is shown in Fig. 3. The mark distribution of test and simulation is in good agreement. The comparison between the test and simulation values is shown in Table 2. Due to the difference in tire pattern structure between the test and simulation, there are relative errors in the length, width and area of the ground mark, with the maximum error of 5.0%, which is within the allowable range of engineering error. Therefore, the simulation model can be used for the next simulation analysis.

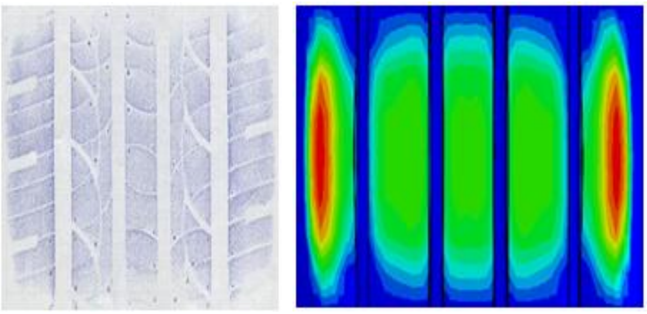

Fig. 3. Shape of grounding trace under static load.

Table 2. Grounding trace test and simulation value.

Ground Imprinting Parameters	Test	Simulation	Relative Error /%
The length of the long axis of the imprint /mm	140.09	143.57	2.5
Short axis length of imprinting /mm	100.10	102.60	2.5
Imprinting area /mm^2	14023	14730	5.0

III. STRUCTURE DESIGN AND EVALUATION INDEX

A. *Structure Design of Tire Crown*

Crown arc is the main parameter that determines the shape of the crown. Improper design will lead to tread deviation wear, insufficient grip and other phenomena, thus affecting the handling performance of tire driving and braking [10]. Generally, b /B is 0.75 ~ 0.8 and h /H is 0.03 ~ 0.05. The tire crown structure is shown in Figure 4.

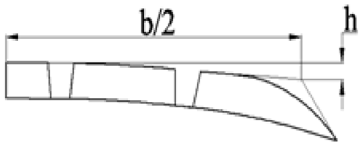

Fig. 4. Crown structure diagram.

In order to alleviate the problems of tire eccentric wear and lack of grip, multi-section arc is widely used in tire crown arc design. The study found that during the movement of cats, the soles of their feet can provide superior grounding performance and the arc of the palm pad is similar to the arc of the tire crown [11]. The cross section curve of the palm pad is shown in Figure 5. Therefore, the cross section curve of the palm pad was analyzed, and the bionic design of the tire crown arc of the shoulder was carried out. Under the premise of not changing the width and height of the tire crown arc, the bionic arc curvature decreases compared with the sample tire design, as shown in Fig. 6.

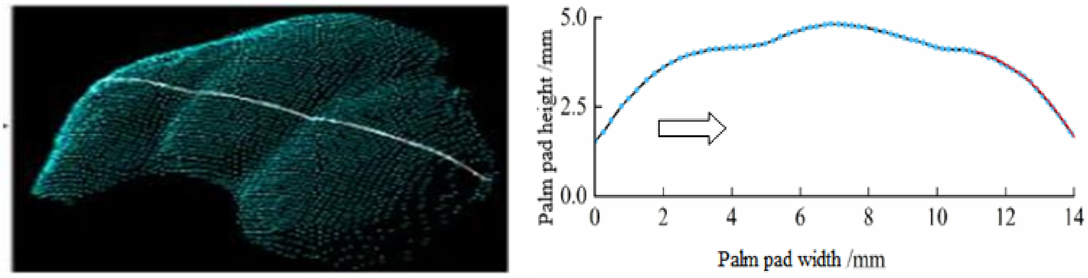

Fig. 5. Cross-sectional graph of palm pad.

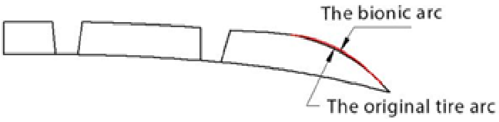

Fig. 6. Schematic diagram of bionic crown arc.

To sum up, based on the size of the sample tire, the width and height of the tire crown arc and the bionic arc structure were designed. The 1/2 arc width is 77, 79 and 81mm respectively, and the arc height is 3.4, 4.5 and 5.6mm respectively. A total of 10 schemes are obtained, among which scheme 5 is the size of sample tire, and scheme 6 is the design size of bionic tire crown arc.

B. *Selection of Evaluation Indexes*

The variation of the tire crown arc has a great influence on the tire grounding performance, so it is necessary to consider several evaluation indexes to characterize the tire grounding performance when designing the tire crown arc structure.

(1) In the process of tire braking, the best grip performance of the tire can be exerted under the condition of optimal slip rate. Therefore, in this paper, the tire-ground support reaction force under the optimal slip rate during braking is used to evaluate the tire's ground grip performance. The slip rate S is expressed as:

$$S = \frac{v - r_d w}{v} \times 100\%$$

(2) Where, r_d is the free rolling radius of the tire, V is the translational speed of the vehicle, and W is the angular speed of the tire. The free rolling radius r_d = 0.3010 m and the angular velocity ω_0 = 53.7721 rad/s were calculated.

(3) Partial wear of tires is the main factor affecting the service life of tires. The reason is that the tire ground pressure distribution is not uniform. Therefore, the earthing pressure standard deviation $f(x)$ is used to indirectly represent the uniformity of tread wear. The smaller the value is, the more uniform the earthing pressure distribution is and the better the wear performance is. Its calculation formula is as follows:

$$f(x) = \sqrt{\frac{1}{n-1}\sum (p_i - \bar{p})^2}$$

(4) Where, n is the number of nodes in the ground imprint, p_i is the pressure value of the i point in the ground imprint, and $\bar{p}$ is the average value of the distributed pressure in the whole ground imprint.

(5) Fatigue failure is the main failure mode of radial tire. The radial tire of passenger car is different from the radial tire of heavy duty in that the working conditions are mostly high-speed driving rather than low-speed

loading, and the damage mainly occurs at the end of the tire shoulder band layer but less in the bead part [12]. The strain energy density amplitude is taken as the durability evaluation index. Its calculation formula is as follows: $W = \frac{dV_\varepsilon}{dV} = \frac{1}{2}(\sigma_1\varepsilon_1 + \sigma_2\varepsilon_2 + \sigma_3\varepsilon_3)$

(6) $SENER_m = W_{\max} - W_{\min}$

(7) Where: σ_i, ω_i, $W_{\max}$ and $W_{\max}$ are the stress, strain, maximum strain energy density and minimum strain energy density of shoulder element respectively.

IV. ANALYSIS AND DISCUSSION OF GROUNDING PERFORMANCE

A. *Analysis of Grip and Wear Performance*

The shape of the crown arc can affect the stress and deformation of the tread from the structure, revealing the influence on the grip and wear performance. 60 km / h is used as the initial speed for 15% slip rate braking. Through the simulation analysis of the above 10 schemes, the simulation data is shown in Table 3.

Table 3. Simulation data of different crown arc structure models.

Package Number	**1/2 arc Width/Height/mm**	**Grounding Area/ mm^2**	**Maximum Grounding Pressure /MPa**	**Traction/N**	**Grounding Pressure Standard Deviation /MPa**
1	77/3.4	14383	0.7109	2973	0.157206
2	77/4.5	14323	0.7169	2960	0.164256
3	77/5.6	14470	0.7322	2950	0.172708
4	79/3.4	14325	0.6785	3006	0.147312
5	79/4.5	14441	0.7111	2989	0.158620
6	79/4.5*	14581	0.7218	2996	0.156315
7	79/5.6	14605	0.7167	2978	0.164490
8	81/3.4	15075	0.6307	3040	0.144549
9	81/4.5	14933	0.6663	3027	0.146785
10	81/5.6	15006	0.6738	3014	0.152419

It can be seen from Table 3 that, under the condition of the same crown arc width, with the increase of crown arc height, the grip gradually decreases, the ground grip performance decreases, the maximum grounding pressure presents an increasing trend, and the standard deviation of grounding pressure gradually increases, and the wear performance decreases. On the contrary, with the increase of the crown arc width, the grip force gradually increased, the ground grip performance improved, the maximum grounding pressure showed a downward trend, and the standard deviation of grounding pressure gradually decreased, and the wear performance improved. In Scheme 6, compared with the sample tire, the bionic tire crown arc design improved the grip, increased the maximum grounding pressure, and reduced the standard deviation of grounding pressure, which alleviated the contradiction between the grip and wear performance to a certain extent. Fig. 7~ Fig. 9 directly reflect the influence of different crown arc designs on the distribution of imprints.

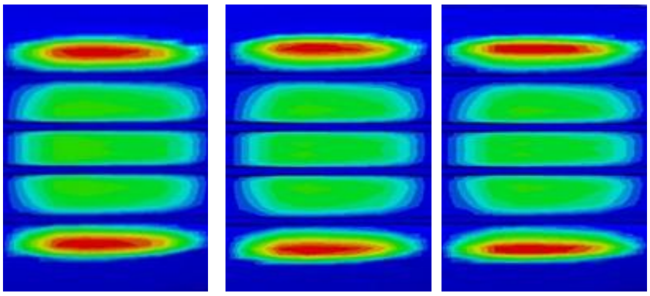

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Fig. 7. Grounding footprint of different crown arc heights.

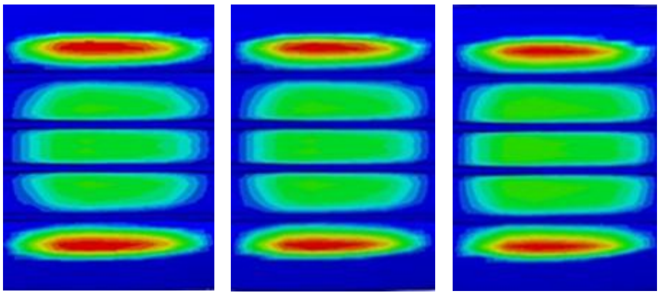

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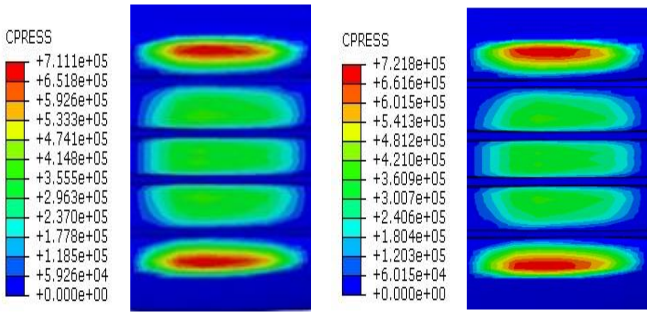
Fig. 8. Grounding footprint with different crown arc widths.



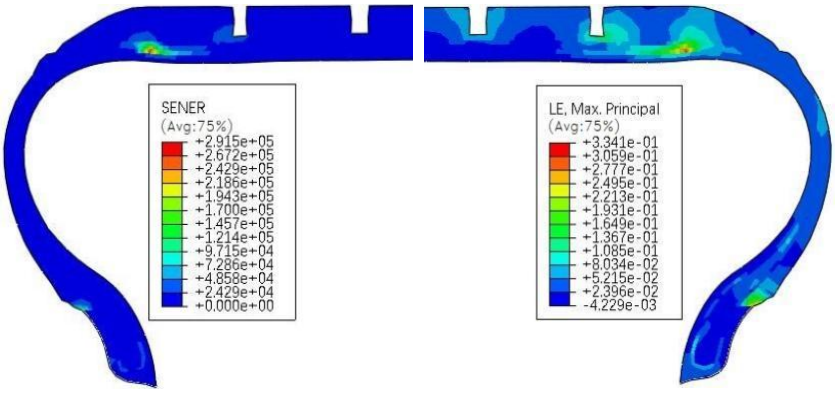
(a) Sample tire (b) Bionic tire

Fig. 9. Comparison of bionic crown arc grounding marks.

Based on Table 3 and Figure 7-9, it can be seen that with the increase of the tire crown arc height, the center area of the earthing mark changed little, but the shape of the earthing mark at the tire shoulder changed from “elliptical” to “long shuttle”, and the high stress area gradually transited to the tire shoulder. As a result, most of the grip force is provided by the shoulder in the high stress area, which increases the standard deviation of grounding pressure and reduces the wear performance. The increase of the tire crown arc width can significantly increase the center area of the earthing mark, increase the “rectangular ratio” of the earthing mark, effectively alleviate the stress concentration at the tire shoulder position, improve the uniform distribution of pressure in the earthing mark, and improve the wear performance. The effect of crown arc width on ground grip and wear performance is greater than that of crown arc height. After the bionic tire crown arc design, the change of the center ground mark area is small, the area of the ground area at the tire shoulder position increases, and the dispersion of the high stress area is better. The contradiction between the tire grip and wear performance can be improved under the premise that the ground mark is basically unchanged.

B. *Durability Analysis*

The passenger car tire is different from the truck radial tire, which mainly focuses on the durability of the shoulder under high speed conditions. On the premise that other parameters remain unchanged, the driving speed under free rolling state is defined as 100 km/h. The strain energy density and strain distribution of the cross section of the grounding center are shown in Fig. 10.



(a) Strain energy density (b) Strain

Fig. 10. Strain energy density and strain distribution in cross section of grounding center.

It can be seen from Figure 10 that the inner contour of the earthing of the shoulder has a concavity trend, and the higher strain energy density is mainly distributed at the end of the shoulder band layer, and a small amount is distributed at the contact part between the end of the rim and the lower body. The contour strain of the ground is mainly distributed at the end of the shoulder band layer, the bottom of the groove, the end of the tire body layer and the contact part between the rim and the lower tire body. It can be seen that even under different evaluation indexes, the tire shoulder position is the main damage prone area. The histogram of strain energy density data and variation trend of shoulder with different crown arc structures are shown in Table 4 and Figure 11, respectively.

Table 4. Durability data of different crown arc structure models.

Package Number	**Strain Energy Density**	
	The Maximum (J·mm-3)	**Amplitude (J·mm-3)**
1	0.29318	0.29314
2	0.28416	0.28413
3	0.28151	0.28148
4	0.29310	0.29307
5	0.29101	0.29097
6	0.29139	0.29135
7	0.28288	0.28285
8	0.29968	0.29964
9	0.29708	0.29705
10	0.29236	0.29233

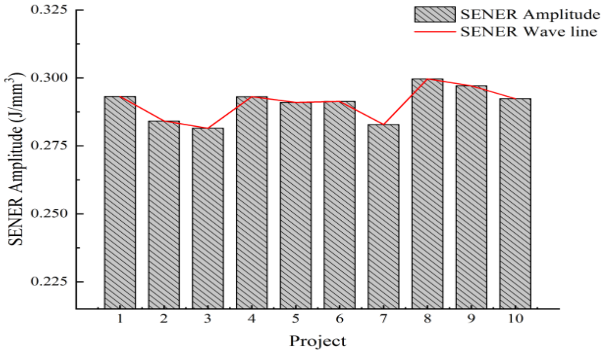


Fig. 11. SENER amplitude under different crown arc structures.

Fig. 11 shows that the height of tire crown arc remains unchanged, and the amplitude of strain energy density presents an increasing trend with the increase of tire crown arc width. However, under the condition of low tire crown arc width (77 mm-79 mm), the change of structural parameters on the amplitude of strain energy density is less than 2%. Under the condition of peak crown arc width (81 mm), it increased but the range was small, which was about 3%. With the increase of the tire crown arc height, the strain energy density amplitude decreased, and the maximum variation range was 3%, but the fluctuation was still small. The strain energy density amplitude of the bionic tire crown arc design increases slightly on the basis of the sample tire structure, but the change is less than 1%, which has little effect on the end durability of the shoulder band layer. In summary, the structural parameters of the tire crown arc have limited influence on the shoulder durability within the value range.

V. CONCLUSION

In this paper, the finite element software was used to build a tire model and the correctness of the model was verified by loading test. The tire crown arc structure was controlled by changing the width b and height h of the tire crown arc, and the bionic tire crown arc design was carried out on the sample tire to explore its influence on the tire grounding performance, and the following conclusions were drawn:

1. The influence of tire crown arc width on the ground grip and wear performance is greater than that of tire crown arc height. With the increase of the crown arc height, the gripping performance decreased, the high stress area of the shoulder increased, and the abnormal wear aggravated. With the increase of the crown arc width, the “rectangular ratio” of the ground mark increased, the ground grip performance improved, the standard deviation of the ground pressure decreased, and the wear performance improved.

2. After the bionic tire crown arc design, the tire can improve the grip and reduce tread wear under the premise of stable grounding mark, and improve the performance of both, and have little effect on the durability of the tire shoulder, which is only about 1%.

3. The influence of crown arc structure parameters on shoulder durability is small, and the influence of crown arc height on shoulder durability is greater than that of crown arc width, which is about 3%. The crown arc parameter is not the main factor affecting shoulder durability.

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