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Analysis of Influencing Factors of Tire Hydroplaning

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***Abstract* – In order to study the influencing factors of tire hydroplaning performance on wet roads, the 205/55 R16 radial tire is used as the research object, and the finite element method is used to simulate the hydroplaning process of the tire. First, the tire finite element model is established, and then the "tire-water-road" finite element model is established using the CEL method to study the influence of water film thickness, vehicle speed, vertical load and tire pressure on tire hydroplaning performance. The results show that the road contact force and road contact area decrease with the increase of water film thickness and speed, and increase with the increase of vertical load and tire pressure. Appropriately reducing the speed and increasing the inflating pressure are helpful to driving safely in rainy weather.**

***Keywords* – Tire Hydroplaning, Coupled Euler-Lagrange (CEL), Wet Road, Radial Tire.**

I. INTRODUCTION

The performance of safe driving on wet roads is the basic requirement for tires. Studies have shown that [1-3], about 20% of road accidents occur in wet weather conditions, and tire hydroplaning is the main cause of accidents. When driving on a wet road, the tire adhesion performance is significantly reduced, and the vehicle is prone to sideslip and out of control, which directly affects driving safety [4, 5]. Therefore, it is of great significance to study the hydroplaning performance of tires.

T.F. Fwa et al. [6] studied the relative effectiveness of road grooving and tire grooving in reducing the risk of vehicle hydroplaning. Y.M. Ding et al. [7, 8] used the CEL method to study the hydroplaning performance of wide-based tires. The results show that the hydroplaning performance of wide-based tires is better than that of conventional radial tires, and the critical hydroplaning speed of tires in free rolling state is higher. Nakajima et al. [9,10]based on the research results of Weiss, used Lagrange formula to conduct finite element analysis on tires and Euler formula to conduct finite volume analysis on fluids to study the hydroplaning phenomenon of complex tire pattern. Kumar et al. [11] used the finite element software ABAQUS to conduct a hydroplaning simulation analysis on smooth tires in pure sliding and pure rolling conditions based on the CEL method, and found that the risk of tire hydroplaning in the pure sliding state of the tire is obviously higher than that of the tire in pure rolling conditions.

Previous studies mainly used a single index such as hydrodynamic pressure or critical hydroplaning speed to study the hydroplaning performance of tires, and there were few factors affecting the hydroplaning performance of tires. The use of multiple indicators of road contact force and tire contact area to study tire hydroplaning can provide a reference for the driver's safe driving from multiple aspects.

Using the finite element analysis method, the 205/55 R16 pneumatic radial tire model, the water film model and the road surface model are established respectively, and then the tire, water film and road model are coupling analyzed using the coupled Euler-Lagrangian method. Based on the finite element model of tire hydroplaning, the road contact force and contact area are used as evaluation indexes to study the influence of different water film thickness, vehicle speed, vertical load and tire pressure on the tire hydroplaning performance.

II. FINITE ELEMENT MODEL OF TIRE HYDROPLANING

A. *Tire Model*

As the most important part of the tire hydroplaning phenomenon, the 205/55 R16 pneumatic radial tire is used as the research object. In the process of building a model and inflating, rotating and loading, the carcass, rim and road need to be considered. In order to simplify the model without affecting the accuracy of the model, the carcass is defined as a variety of rubber and cord composite materials, and the rim is replaced by a simplified two-dimensional surface element, and the road is defined as an indeformable rigid body.

First of all, draw the tire two-dimensional sectional view in AutoCAD. The profile is imported into the Hypermesh to divide the 2D mesh according to the tire structure. Second, the 2D mesh is imported into ABAQUS and material parameters of rubber and cord are given. The superplastic Neo-Hookean model is used to describe the mechanical properties of rubber. For the parts containing stiffeners such as the band layer and the cord layer, the embedded Rebar element is used to simulate the mechanical properties. The initial Angle, cross-sectional area and stiffener spacing of the Rebar layer could also be set. Finally, the 3D finite element model of the tire is generated in ABAQUS, as shown in Fig. 1.

Fig. 1. Finite element model of tire.

B. *Euler Water Film Model*

The Euler water film model is established in Abaqus/CAE. The model is composed of Euler grids, as shown in Fig. 2. In the actual driving process, the tire rolls over the water-filled road at high speed, and the water spreads under the high-speed impact of the tire. The water impact model is used in the simulation. The water impact model refers to the conversion of the relative motion coordinate system to convert the forward motion of the tire into the water current impacting the rotating tire at the same speed and opposite direction. The advantage of this model is to reduce the number of Euler model grids and speed up the calculation. Through the setting of boundary conditions, the water flows in from the front end of the model and flows out from the back end of the model. The lower part of the initial Euler model is a water layer, which is divided into 3 layers of grids, the thickness of the water film is 10 mm, and the upper part is a reserved air layer, which is divided into 5 layers of grids with a thickness of 50 mm, and the number of grids is 561600.

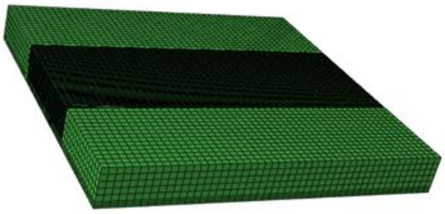


Fig. 2. Euler water film model.

C. *Fluid-Structure Coupling Setup*

When a vehicle drives over a water-filled road at high speed, the tire not only generates stress and strain under the action of the road, but also produces complex coupling deformation with the water film under the action of hydrodynamic pressure. Due to the complex interaction between tires and water film, coupled Euler-Lagrangian (CEL) is needed to solve this problem. For tires, a Lagrangian grid is used, and the grid deforms as the tire deforms. For water film, Euler grid is used, and the grid position is fixed in space. The problem of coupling between tires and water flow is solved by using general contacts for the two grids.

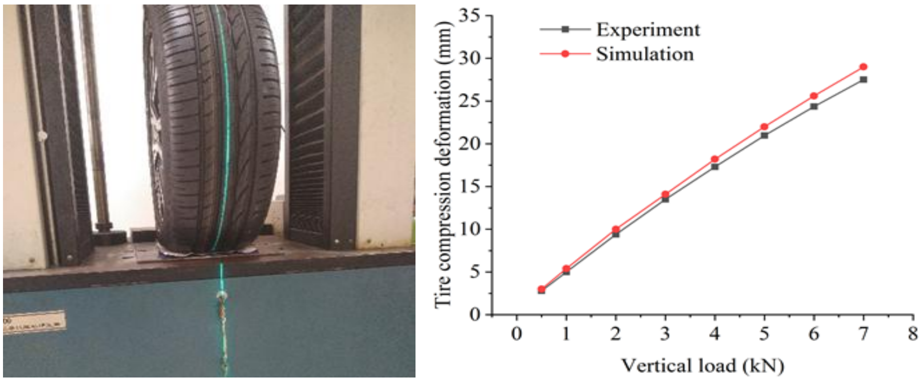
III. MODEL VALIDATION

A. *Flow Tire Model Validation*

Accurate modeling of tires is an important step to obtain reliable simulation results. The reliability of the tire model is verified by comparing the simulation results with the test results.

Firstly, a 250kPa tire is left standing at indoor temperature for 24 hours. Secondly, the CSS-88100 static loading test machine is used to carry out vertical loading tests on the tires, with loads from 0.5kN to 7kN, as shown in Fig. 3 (a). Finally, the experiment is repeated several times and the results are averaged.

Firstly, 250kPa pressure is applied to the inner surface of the tire and the rim is secured in ABAQUS. Secondly, the corresponding vertical load is applied to the tire. Finally, the compression deformation of the tire is obtained and compared with the experimental results, as shown in Fig. 3 (b). It can be seen from the figure that the tire compression deformation has an approximate linear relationship with the load, and the error between test and simulation is very small (the maximum is 3.56%), indicating that the simulation model has high reliability.



(a) The CSS-88100 static loading test machine.
(b) Load-tire compression deformation curve.

Fig. 3. Model validation.

B. *Tire Hydroplaning Model Validation*

Due to the limitation of test conditions, some empirical equations are usually used to verify the hydroplaning model. Among them, the NASA hydroplaning equation proposed by Horne et al. in 1963 is the most commonly used. However, this equation only considers the influence of tire pressure on hydroplaning performance, which is quite different from the actual situation. In 1986, Horne [12] proposed an empirical equation considering the tire pressure and the aspect ratio of the tire footprint:

$$v = 25.01 p^{0.21} \left(\frac{1.4}{FAR} \right)^{0.5} \tag{1}$$

In the equation, v is the critical hydroplaning speed, in km/h; p is the tire pressure, in kPa; *FAR* is the ratio of the width to the length of the tire footprint. In this simulation analysis, the tire pressure is 250 kPa, the ground contact width is 155 mm, and the ground contact length is 118 mm. Substituting into equation (1), the critical waterskiing speed is 82.32 km/h. The difference between the critical hydroplaning speed of 76.82km/h and the tire hydroplaning model is 6.68%, indicating that the hydroplaning results obtained by the tire hydroplaning model have a high degree of credibility.

IV. RESULTS AND DISCUSSION

A. *The Influence of Water Film Thickness on Hydroplaning Performance*

Keeping the tire pressure of 250 kPa, the load of 3700 N, and the speed of 75 km/h unchanged, the road contact force and contact area of the tire hydroplaning model are obtained when the water film thickness is 5 mm, 7.50 mm, and 10 mm, as shown in Fig. 4. As the thickness of the water film increases, the contact force and contact area between the tire and the road are gradually decreasing, and the hydroplaning performance of the tire decreases. When the thickness of the water film is greater than 7.50 mm, the drop rate increases. The reason is that when the thickness of the water film exceeds the depth of the groove, the drainage capacity of the groove is greatly reduced, resulting in more serious water accumulation at the front end of the tire. The greater the thickness of the water film, the more likely the car will be hydroplaning, and the greater the risk of traffic accidents.

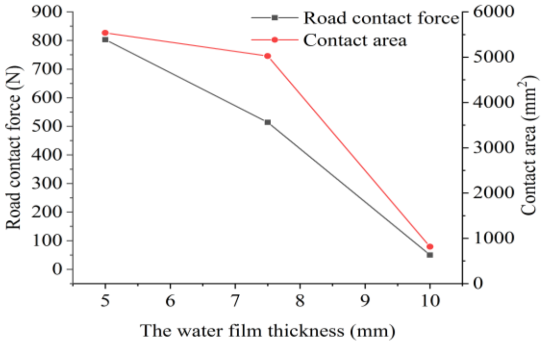


Fig. 4. Road contact force and contact area at different water film thicknesses.

B. *The Influence of Vehicle Speed on Hydroplaning Performance*

Keeping the tire pressure of 250 kPa, the load of 3700 N and the thickness of 10 mm water film unchanged, the road contact force and contact area of the tire hydroplaning model are obtained when the vehicle speed is 70 km/h, 75 km/h and 80 km/h, as shown in Fig. 5. It can be seen that as the speed increases, the road contact force and contact area decrease sharply. At a speed of 70 km/h, the road contact force and contact area are 989 N and 6172 mm^2, which are 73.31% and 57.65% respectively lower than those of driving on dry roads. At a speed of 75 km/h, the road contact force and contact area dropped to 50 N and 814 mm^2, indicating that the tire no longer has the normal driving ability at this time. When the water speed reaches 80 km/h, the road contact force and contact area both drop to zero, indicating that the tire has experienced hydroplaning at this time. It shows that as the driving speed increases, the hydroplaning performance of the tire decreases. Therefore, when driving in rainy weather, the driver can ensure driving safety by appropriately reducing the speed of the vehicle.

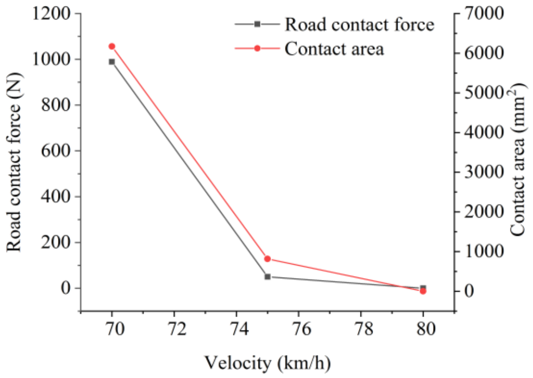


Fig. 5. Road contact force and contact area at different vehicle speeds.

C. *The Influence of Vertical Load on Hydroplaning Performance*

Keeping the tire pressure of 250 kPa, the speed of 75 km/h and the thickness of 10 mm water film unchanged, the road contact force and contact area of the tire hydroplaning model are obtained when the vertical load is 3400 N, 3700 N and 4000 N, as shown in Fig. 6. It can be seen that as the tire load increases, the road contact force and contact area increase sharply and the hydroplaning performance of the tire also increases significantly. As the tire load increases, the drainage capacity of the tire increases accordingly, and the hydrodynamic pressure required to reach the critical hydroplaning state also increases. When the tire load is 4000N, the road contact force is 312N, and the contact area is 3491mm^2, which is only 7.80% and 18.05% of the dry road. At this time, the car is still in a dangerous state, and the risk of accidents is still high. Therefore, the driver needs to reduce the speed as much as possible to maintain a safe distance when driving in rain.

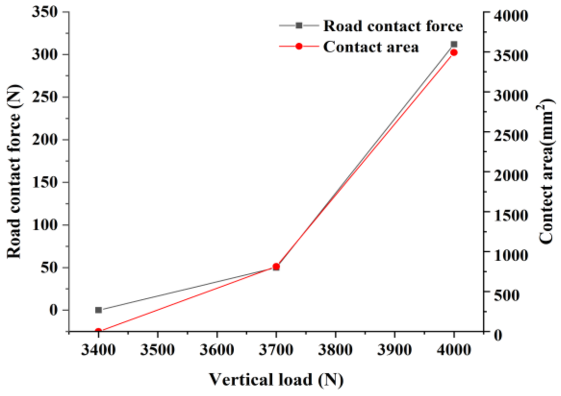


Fig. 6. Road contact force and contact area at different vertical loads.

D. *The Influence of Tire Pressure on Hydroplaning Performance*

Keeping the load of 3700 N, the speed of 75 km/h and the thickness of 10 mm water film unchanged, the road contact force and contact area of the tire hydroplaning model are obtained when the tire pressure is 220 kPa, 250 kPa and 280 kPa, as shown in Fig. 7. It can be seen that as the tire pressure increases, the road contact force and contact area also increase. As the inflation pressure increases, the tire stiffness increases. Under the same hydrodynamic pressure, the tire deformation decreases, the drainage capacity of the grooves also increases, and the hydroplaning capacity of the tire also increases. Therefore, when driving on rainy weather, the driver needs to pay attention to the tire pressure. Appropriately increasing the tire pressure will help improve the hydroplaning ability of the tire.

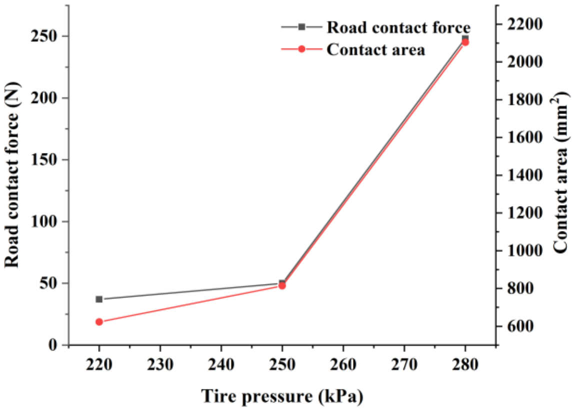


Fig. 7. Road contact force and contact area at different tire pressures.

V. CONCLUSION

The CEL method is used in Abaqus to study the influence of water film thickness, vehicle speed, vertical load and tire pressure on the hydroplaning performance of the tire on the wet road, and the following conclusions are obtained.

(1) The greater the water film thickness, the worse the hydroplaning performance of the tire. When the thickness of the water film exceeds the depth of the groove, the drainage capacity of the tire is greatly reduced, and the hydroplaning performance of the tire deteriorates sharply.

(2) As the driving speed increases, the road contact force and contact area decrease, and the hydroplaning performance of the tire decreases. Therefore, when driving in rainy weather, the driver can ensure driving safety by appropriately reducing the speed of the vehicle.

(3) As the vertical load increases, the current lifting force required to reach the critical hydroplaning state increases, and the tire's critical hydroplaning speed increases accordingly.

(4) As the tire pressure increases, the tire stiffness increases, tire deformation decreases, and hydroplaning performance improves. Properly increasing the tire pressure will help drive safely in rainy weather.

REFERENCES

[1] Okano T., Koishi M.A. new computational procedure to predict transient hydroplaning performance of a tire. Tire science and Technology, 2001, 29(1): 2-22.
[2] Horne, W.B., Joyner U.T. Pneumatic Tire Hydroplaning and Some Effects on Vehicle Performance. 1966, 74:623-650.
[3] Horne, W.B., and U.T. Joyner. Pneumatic Tire Hydroplaning and Some Effects on Vehicle Performance. In SAE International Automotive Engineering Congress. Detroit, Mich., 1965.
[4] Grogger H, Weiss M. Calculation of the hydroplaning of a deformable smooth-shaped and longitudinally-grooved Tire. Tire Science and Technology, 1997, 25(4): 265-287.

[5] Grogger H, Weiss M. Calculation of the three-dimensional free surface flow around an automobile tire. Tire Science and Technology, 1996, 24(1): 39-49.
[6] Kumar S S, Kumar A, Fwa T F. Analyzing effect of tire groove patterns on hydroplaning speed. Journal of the Eastern Asia Society for Transportatio Studies, 2009, 8: 2018-2031.
[7] Y. M. Ding, H. Wang. Computational investigation of hydroplaning risk of wide-base truck tyres on roadway. International Journal of Pavement Engineering, 2020, 21(1).
[8] Y.M. Ding, H. Wang. Evaluation of Hydroplaning Risk on Permeable Friction Course using Tire–Water–Pavement Interaction Model. Transportation research record, 2018, 2672(40).
[9] Nakajima Y, Seta E. Hydroplaning analysis by FEM and FVM, effect of tire rolling and tire pattern on hydroplaning. International Journal of Automatic Techno logy, 2000, 1(1): 26-34.
[10] Seta E, Nakajimay, Kamegawa T, et al. Hydroplaning analysis by FEM and FVM: effect of tire rolling and tire pattern on hydroplaning. Tire Science and Technology, 2000, 28(3): 140-156.
[11] Srirangam Santosh Kumar,Kumar Anupam, Tom Scarpas, Cor Kasbergen. Study of Hydroplaning Risk on Rolling and Sliding Passenger Car. Procedia - Social and Behavioral Sciences,2012,53.
[12] Horne, W.B., Yager, T.J. and Ivey, D.L. Recent Studies to Investigate Effects of Tire Footprint Ratio on Dynamic Hydroplaning Speed [J]. The Tire Pavement Interface, pp. 26–46, ASTM STP 929, ASTM, Philadelphia, 1986.

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