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Simulation Analysis of Tire Hydroplaning Performance Based on CFD

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***Abstract* – In rainy weather, the road surface will form a water film due to the accumulation of rainwater, which will easily cause the car to skid and lose control, resulting in traffic accidents. Therefore, it becomes very meaningful to study the hydroplaning performance of tires. In this paper, we take 185/60 R15 radial tire as the research object and use CATIA software to draw radial tires with five patterns (slick tyres, transverse tire, longitudinal tire, transverse complex tire and diagonal complex tire) and construct Boolean reduction model. The geometric processing of fluid domain and mesh division are completed in ANSYS software, and after the mesh quality check, four speeds of 20 m/s, 23.3 m/s, 26.6 m/s and 30 m/s are set for the entrance, and SIMPLEC algorithm is determined for simulation calculation to characterize the tire's hydroplaning performance on the waterlogged road with dynamic water pressure as the evaluation index, so as to determine the best tread structure and the results show that the tire can be used at 20-30 m. The results show that the diagonal complex tire has the best data in the speed range of 20-30 m/s.**

***Keywords* – Tire Tread Pattern, Hydroplaning Characteristics, Dynamic Water Pressure, Computational Fluid Dynamics, Structure Optimization.**

I. INTRODUCTION

According to incomplete statistics, the number of traffic accidents caused by tire factors accounts for 50% of the total number of traffic accidents. When driving a car at the specified speed in rain and snow, the wheels are prone to slickness due to the water that appears between the tread and the ground, which in turn reduces the adhesion coefficient and braking effect of the car on the ground, which will seriously affect the stability of the car and the work safety of the driver and occupants. Therefore, it is an urgent problem to improve the stability of the car driving on wet roads.

Since the introduction of pneumatic tires in 1888, many researchers at home and abroad have never stopped their research on tires. Browne et al [1] considered the effects of water viscosity, inertia and turbulence and used the Navier-Stokes equations to reduce the three-dimensional flow to a two-dimensional problem to establish a coupled tire-fluid model. Fwa and Ong et al [2] investigated the effect of spacing, depth, and width of transverse grooves in pavements on the critical hydroplaning velocity of tires. Horne et al [3] through a series of tire water skiing tests, found that the tire in water skiing its grounding area gradually becomes smaller, the tread dynamic water pressure increases, the rotational angular velocity becomes smaller, etc., and collected experimental data to summarize the water skiing empirical formula that can reflect the critical speed of water skiing. Wies et al [4] carried out several groups of front and rear drive cars on waterlogged roads in straight and side-slip tests, and summarized the experimental results to explore the extent to which the various geometric features of tread grooves affect the water-slip characteristics of the tires. Jizhong Wang , Jide Zhuang et al [5,6] simplified tire hydroplaning on waterlogged roads to the problem of extrusion of water film by the tire unit based on hydrodynamic lubrication theory, and studied the influence of each parameter on tire viscous hydroplaning and wet traction performance. Tianjian Ji et al [7] established the Reynolds equation, geometric equation and load balance equation for the hydroplaning phenomenon based on the elastic lubrication theory to analyze tire dynamic hydroplaning and construct a regression model of water film thickness and hydroplaning velocity. Ting Feng [8] abstracted the tire hydroplaning phenomenon as a lubrication system composed of tire, water film and road surface based on elastic flow lubrication theory, constructed a mathematical model, and analyzed the effect of speed and load on hydroplaning performance through programming calculation. Aiqin Shen et al [9] measured the dynamic water pressure on the pavement by placing a high-frequency pressure sensor under the water film, and then used COMSOL software to build a simulation model to study the influencing factors of the dynamic water pressure on the pavement. Guolin Wang et al [10] used CFD method to study the external flow field of tire water skiing and found that the method can accurately capture the internal smooth changes of water flow during the water skiing process. Yue Li et al [11] took the main landing gear of Airbus A320 as the research object, established a two-wheel wheel set-waterlogged road surface flow-solid coupling slick water analysis model, and analyzed the law of the road surface water additional drag influence factors.

Many scholars at home and abroad have conducted a large number of simulations and experimental studies on tire water-sliding, and tire tread improvement has been explored, and numerous results have been achieved. However, there is still a need to continue research in improving water-slide performance. This paper mainly focuses on the simulation analysis of five types of tread structure: bare tire, transverse tread, longitudinal tread, transverse complex tread and diagonal complex tread. Based on the simulation results such as dynamic water pressure, the hydroplaning performance is judged and the pattern structure is optimized to improve the hydroplaning performance of the tire.

II. Model Building

A. *Tire Hydroplaning Fluid Domain Modeling*

Firstly, draw a 2D single pitch section of 185 tire in CAD and import it into CATIA software to complete the sketch positioning according to the positioning line. After finishing the sketch positioning, use the rotation, circular array and other operations to draw the tire solids of slick tyres, transverse tire, longitudinal tire, transverse complex tire and oblique complex tire. Figure 2.1 shows the geometrically processed fluid domain model of five types of radial tires.

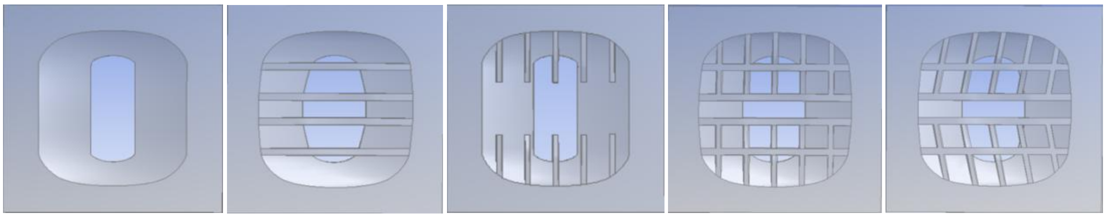


Fig. 2.1. Geometrically processed Boolean subtraction model.

B. *Fluid Domain Boundary Condition Setting*

The inlet fluid of the fluid domain model is set to water, and the boundary conditions should be set to ensure that no water will enter inside the tire. The boundary conditions are set in fluent as shown in figure 2.2.

Fluid Inlet:

The tire water slide phenomenon is most likely to occur at a speed of 25 m/s. Therefore, each fluid domain m-

-odel should set four speeds of 20 m/s, 23.3 m/s, 26.6 m/s, and 30 m/s at the inlet, and compare the data after the simulation calculation is finished for each data. In setting the boundary conditions, the situation is as follows.

Pressure Outlet:

Set the fluid outlet and the two sides of the fluid domain model as pressure outlet.

Wall Surface:

The bottom and top of the fluid domain model are designed as sliding wall surface without shear stress.

Coupling Surface:

Set the contact surface between the fluid domain model and the tire as the mechanical analysis plane between the wheels of the water layer.

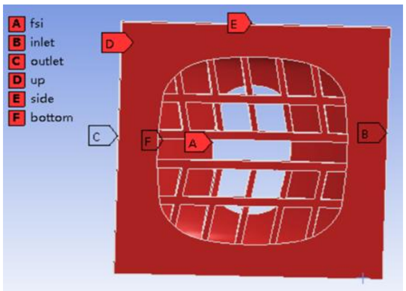


Fig. 2.2. Fluid domain model boundary conditions.

III. Comparative Analysis of Simulation Results for Each Tread Pattern Tire

A. *Analysis of Resistance Reduction Rate of Different Tread Pattern Tires*

The difference in drag reduction characteristics of different tread pattern tires can be determined by the drag reduction rate. The shear stress values on the surface of the tread grooves at different speeds are compared to obtain the subspeed drag reduction rate *R* at five speeds, which is calculated as follows:

$$R = \frac{(\tau_s - \tau_g)}{\tau_s} \times 100\% \quad (1)$$

In which, τ_s and τ_g are the shear stress between the slick tyres and other tread tires respectively. If $R>0$, it means that the pattern tire has drag reduction effect, and the larger the value of *R*, the better the drag reduction effect; if $R<0$, it means that the pattern tire has drag increase characteristic, and the larger the value, the more obvious the drag increase; if $R=0$, it means that the pattern tire has no drag reduction effect. The resistance reduction values of each pattern model at different incoming flow rates were simulated by Fluent software, as shown in Table 3.1.

Table 3.1. Model resistance reduction rate for each tread pattern tire.

Velocity (m/s)	Pattern Type	Shear Stress (Pa)	Resistance Reduction Rate (%)
20 m/s	slick tyres	1325.01	0
	transverse tire	1242.22	6.25
	longitudinal tire	1225.91	7.48

Velocity (m/s)	Pattern Type	Shear Stress (Pa)	Resistance Reduction Rate (%)
	transverse complex tire	829.58	37.39
	oblique complex tire	817.61	38.29
23.3 m/s	slick tyres	1835.59	0
	transverse tire	1702.21	7.27
	longitudinal tire	1663.98	9.35
	transverse complex tire	1127.19	38.59
	oblique complex tire	1103.69	39.87
26.6 m/s	slick tyres	2484.12	0
	transverse tire	2285.00	8.01
	longitudinal tire	2063.70	16.92
	transverse complex tire	1442.21	41.94
	oblique complex tire	1409.51	43.25
30 m/s	slick tyres	2951.24	0
	transverse tire	2818.05	4.51
	longitudinal tire	2626.06	11.02
	transverse complex tire	1763.71	40.24
	oblique complex tire	1752.78	40.61

According to Table 3.1 to get the different tread pattern tire shear reduction rate comparison. As shown in Figure 3.1, the results show that: at the same speed, the shear stress of the diagonal complex tire is the smallest, the transverse complex tire is basically the same with it, the shear stress of the longitudinal, transverse and slick tires is greater, and the shear stress of each tire increases with the increase of speed.

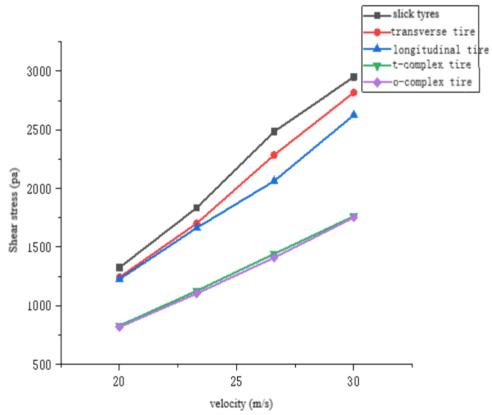


Fig. 3.1. Comparison of shear stress of each pattern.

B. *Dynamic Water Pressure Analysis of Different Tread Tires*

The problem of slick water is considered to be a problem of dynamic water pressure generated by the compression of the water film in the area where the tire is in contact with the road by the tire, and when the dynamic water pressure reaches a specific magnitude, it lifts the tire. Because of the dynamic water pressure, the tire will float up, in a way, the tire and the road certainly can not completely contact, which will reduce the tire traction. In addition, it also affects the vehicle driving speed and safety performance. This is especially true for high-speed, heavy-duty driving conditions. This is extremely detrimental to traffic safety. Therefore, the greater the dynamic water pressure on the tire, the more significant the phenomenon of water-sliding, the worse the water-sliding characteristics.

Table 3.2. Dynamic water pressure of each tread pattern tire at different speeds.

Velocity (m/s)	Pattern Type	Dynamic Water Pressure (kPa)	Rate of Change (%)
20 m/s	slick tyres	321.97	0
	transverse tire	302.97	5.90
	longitudinal tire	263.88	18.04
	transverse complex tire	160.06	50.29
	oblique complex tire	147.65	54.14
	slick tyres	457.36	0
	transverse tire	418.26	8.55
23.3 m/s	longitudinal tire	374.88	18.05
	transverse complex tire	221.69	51.53
	oblique complex tire	204.26	55.34
26.6 m/s	slick tyres	603.10	0
	transverse tire	538.19	10.76
	longitudinal tire	483.21	19.88
	transverse complex tire	290.60	51.82
	oblique complex tire	266.28	55.56
30 m/s	slick tyres	711.06	0
	transverse tire	664.64	5.21
	longitudinal tire	620.78	12.70
	transverse complex tire	363.46	48.88
	oblique complex tire	339.51	52.25

Table 3.2 shows the dynamic water pressure of different patterns at different water velocities. Dynamic pressure is the fluid flow process is affected by resistance, its kinetic energy into pressure energy, that is, the greater the dynamic pressure, the greater the resistance to water flow, speed loss increases, energy loss becomes higher. As can be seen from the table, when the water flow speed is accelerated, the dynamic water pressure within different treads are becoming larger. When the same inlet velocity, complex tires have the lowest dynamic water pressure, which is smaller than that of single pattern or no pattern tires, and the highest dynamic water pressure of light tires. The results show that the complex tread pattern can effectively reduce the tread water pressure.

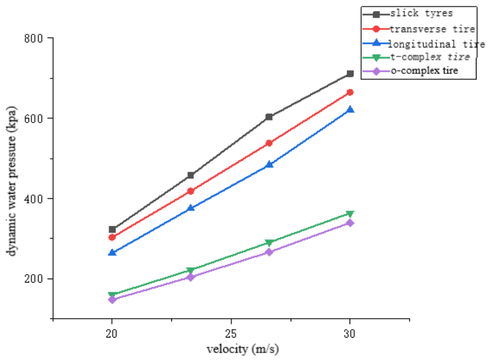


Fig. 3.2. Comparison of dynamic water pressure for each pattern.

IV. Hydroplaning Performance and Optimization Analysis of Each Tread Pattern Tire

A. *Cloud Analysis of Different Tread Pattern Tires*

The dynamic water pressure of the fluid can be used as an evaluation index to evaluate the difference of the slick water performance between different pattern structures. Figure 4.1 shows the cloud diagram of dynamic water pressure distribution for longitudinal, transverse complex and oblique complex tires at 26.6 m/s.

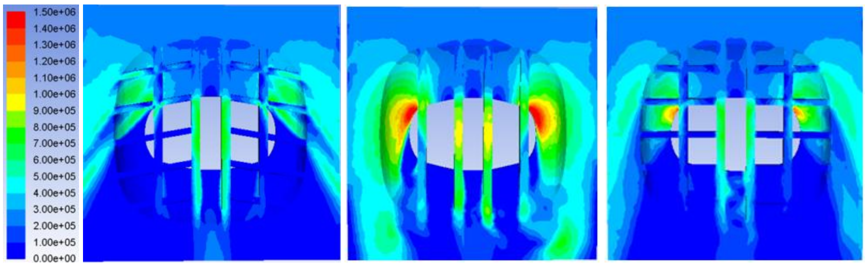


Fig. 4.1. Dynamic water pressure clouds for longitudinal, transverse complex tires and oblique complex tires at 26.6 m/s.

By comparing the clouds, it can be found that the oblique complex tires have the smallest dynamic water pressure and the least high-pressure area; the transverse complex tires have a slightly larger dynamic water pressure, but the difference is not significant; the longitudinal grooves have significantly the largest dynamic water pressure and more high-pressure area in comparison. This is because, after the fluid flows in through the entrance, the central longitudinal groove its main drainage role, easy to become a high-pressure area, the color is redder; but complex tires additionally have slanting grooves or cross grooves, even if the water flows mainly from the longitudinal groove, slanting grooves or cross grooves will also have water flowing out, the number of grooves will increase the dynamic water pressure decreases, high-pressure area reduced. In the fluid domain model, the dynamic water pressure in the middle region is high due to gravity and other reasons, which will affect the cloud observation. In order to exclude this interference factor, the plane will be panned when building the Boolean reduction model in the previous CATIA software, and the bottom surface of the model will be cut 3 mm first, and the bottom will be hollowed out and then made up 3 mm, which will remove the middle high-pressure area and reduce the interference to the experimental results.

By analyzing the cloud diagram of 26.6 m/s, it can be obtained that the existence of transverse and oblique grooves improves the fluidity of water flowing through the fluid domain, reduces the dynamic water pressure and improves the water-sliding performance. And the oblique complex tire groove compared with the transverse complex tire groove, it can be found that after the fluid enters the fluid domain, the direction of the oblique groove is consistent with the fluid direction, which can moderate the water flow pressure at the junction of the groove and has a diversion effect, which can reduce the dynamic water pressure. While the transverse complex tire cross groove does not have a diversion effect, its dynamic water pressure is slightly larger than the oblique complex tire. The angle of the slanting groove can be changed, simulation analysis and then cloud comparison to observe the change of dynamic water pressure under different slanting grooves.

B. *Shear Stress and Resistance Reduction Analysis*

In comparing the analysis of shear stress and drag reduction rate of each tread pattern tire at four speeds, it can be seen that the shear stress increases with the increase of speed, and among the five tread pattern tires, the shear stress of the diagonal complex tire is the smallest. At 20 m/s, the shear stress is the smallest, but the tire drag reduction rate is also not large. By comparison, it is found that the resistance reduction rate of the same pattern tire is similar at 23.3 m/s and 26.6 m/s. Therefore, an additional set of simulation data was added to calculate the shear stress and drag reduction rate values for each tread pattern tire at 25 m/s. The results are shown in Table 4.1.

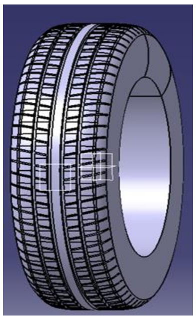
Table 4.1. Shear stress and its resistance reduction rate values for each tread pattern tire at 25 m/s.

Velocity(m/s)	Pattern Type	Shear Stress (Pa)	Resistance Reduction Rate (%)
25 m/s	slick tyres	2168.57	0
	transverse tire	1966.46	9.32
	longitudinal tire	1828.54	15.68
	transverse complex tire	1293.12	40.37
	oblique complex tire	1267.96	41.53

The data in the table shows that the drag reduction rate of each tread at 25 m/s speed is higher than all other speeds, the shear stress is smaller than the data at 26.6 m/s and 30 m/s, and the drag reduction rate of the diagonal complex tire is the highest and the drag reduction effect is the best. Therefore, when driving on rainy days on the highway, you can drive at a speed of about 25 m/s.

C. *Dynamic Water Pressure Optimization Analysis*

After comparing the dynamic water pressure clouds of longitudinal tires, transverse complex tires, and oblique complex tires, we learned that the clouds of complex tires are better, with less dynamic water pressure and fewer high-pressure areas. And in the two kinds of complex tires oblique complex tires have better data, the difference between the two kinds of tires' data is because after the fluid flows in from the inlet, the oblique grooves of the oblique complex tires are in the same direction as the fluid, which can moderate the water pressure at the junction of the grooves and have a diversion effect, which can make the dynamic water pressure lower. The cross groove of the transverse complex tire does not have a diversion effect, and its dynamic water pressure is slightly greater than that of the oblique complex tire. From this can be judged, changing the cross groove direction of complex pattern, can also change the dynamic water pressure, and thus improve the waterslide performance.



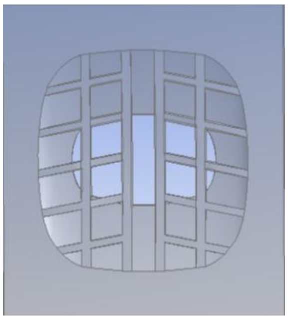


Fig. 4.2. Improved diagonal complex tire model. Fig. 4.3. Geometrically processed fluid domain model.

As shown in Figure 4.2, CATIA software was used to properly change the angle of the slant groove in the slant complex tire. The slant groove angle of the previous slant complex tire was 10°, and the optimized tire slant groove angle was 12.5° to make the angle between the slant groove and the vertical groove smaller. The complete model of the tire is recreated, and then the subsequent operations are carried out, as shown in Figure 4.3, which shows the fluid domain model after geometry processing in Geometry.

After meshing, the minimum orthogonal mass and maximum tilt are found to be different from the minimum orthogonal mass before the change when the mesh quality check is performed. After that, the simulation is performed with the same calculation method with the entrance velocity set to 25 m/s.

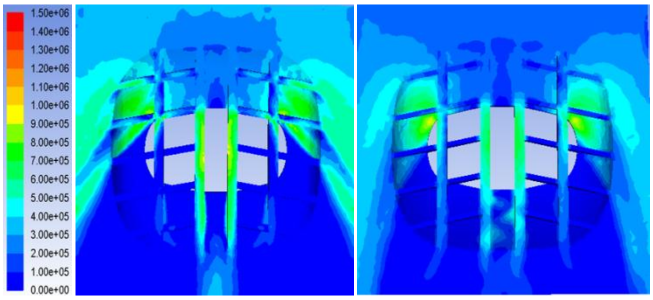


Fig. 4.4. Oblique complex tire clouds before and after optimization.

As shown in Figure 4.4, the dynamic water pressure distribution clouds of two oblique complex tires at 25 m/s speed are shown. By comparing the clouds, the dynamic water pressure of the modified tire is reduced and the high pressure area is also reduced compared with that before the angle modification. This is due to the fact that reducing the angle between the diagonal groove and the longitudinal groove improves the flow of water through the middle longitudinal groove, eases the drainage burden of the fluid domain model, reduces the dynamic water pressure, and thus improves the hydroplaning performance. However, it is also found from the cloud diagram that if the angle of the slanting channel is too large, the dynamic water pressure at the junction of the slanting channel and the cross channel will also be large. Therefore, the angle of the inclined trench should not be too large, otherwise it will also affect the dynamic water pressure in a certain area.

V. Conclusion

(1) A radial tire of 185/60 R15 was taken as the research object and five kinds of tread pattern tires were drawn in CATIA software by rotating and other operations: bare tire, horizontal tire, longitudinal tire, transverse complex tire, and diagonal complex tire. Then the fluid domain model of the five tread pattern tires was obtained by Boolean subtraction operation afterwards.

(2) The water-sliding problem of tires was investigated by CFD method. The calculation method of SIMPLEC is determined, and the inlet velocity is set to four speeds of 20 m/s, 23.3 m/s, 26.6 m/s, and 30 m/s. After initialization, the calculation is carried out, and the simulation results of five tread tires are obtained.

(3) By analyzing the shear stress and drag reduction rate and dynamic water pressure of each tread pattern tire, it was found that the data of the diagonal complex tire were optimal. By analyzing the simulation analysis of shear stress, it was found that the shear stress increased with the increase of speed, and the drag reduction rate increased and then decreased with the speed. Later, through optimization analysis, it was found that the resistance reduction rate was the largest and the best at 25 m/s. After comparing the dynamic water pressure clouds of longitudinal tire, transverse complex tire and oblique complex tire, it is found that the complex tire has less high-pressure area and less dynamic water pressure. After changing the angle of the oblique groove from 10° to 12.5° and then conducting simulation analysis, the results show that appropriately reducing the angle between the oblique groove and the longitudinal groove can reduce the dynamic water pressure and enhance the tire's anti-slip water performance.

REFERENCES

[1] Browne A L. Tire deformation during dynamic hydroplaning [J]. Tire Science and Technology, 1975, 3(1): 16~28.
[2] Fwa T.F., Ong G.P. Transverse pavement grooving against hydroplaning: design [J]. Journal of Transportation Engineering, 2006, 132(6): 449-457.
[3] Horne W.B., Dreher R.C. Phenomena of pneumatic tire hydroplaning [Z]. Technical Note D-2056, National Aeronautics and Space Administration, 1963.
[4] Wies B, Roeger B, Mundl R. Influence of pattern void on hydroplaning and related target conflicts [J]. Tire Science and Technology, 2009, 37(3): 187-206.
[5] Jide Zhuang, Jizhong Wang. Analysis of the effect of tread unit on the sticky water-slide performance of tires [J]. Journal of Agricultural Engineering, 1999, 15(03): 60-64.
[6] Jide Zhuang, Richun Li, Jizhong Wang. Effect of tread unit on wet traction performance of tire film [J]. Automotive Technology, 1998, 16(12): 4-6+56.
[7] Tianjian Ji, Yufeng Gao, Rongsheng Chen. Analysis of power slick of car tires [J]. Journal of Transportation Engineering, 2010, 10(05): 57-60.
[8] Ting Feng. Research on the mechanism of tire hydroplaning on wet pavement [D]. Qingdao University of Technology, 2018.
[9] Aiqin Shen, Pan Song, Yinchuan Guo, Peng Li. Numerical simulation analysis of transient dynamic water pressure at road surface based on COMSOL Multiphysics [J]. Journal of South China University of Technology (Natural Science Edition), 2018, 46(11): 92-101.
[10] Guolin Wang, Liang Jin. Research on CFD calculation method for tire water sliding [J]. Journal of Computational Mechanics, 2012, 29(04): 594-598.
[11] Yue Li et al. Water-slide behavior of aircraft wheel sets and additional resistance of road surface water [J]. Journal of Beijing University of Aeronautics and Astronautics, 2021: 1-13.

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