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Study on Numerical Calculation Method of Tire Hydroplaning

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Abstract **– Taking 205/55 R16 radial tire as the research object, the two most commonly used calculation methods of hydroplaning simulation are studied. Firstly, the three dimensional finite element model of "tire - water – road" is established and verified, and then the finite element analysis of tire hydroplaning process is carried out by using two methods respectively. The results show that the Coupled Euler-Lagrange (CEL)method is more advantageous in the macroscopic analysis of the tire hydroplaning, while the Computational Fluid Dynamics (CFD) method can analyze the tire hydroplaning based on the flow field characteristics, and the research idea combining the two methods can analyze the tire hydroplaning in a more detailed and comprehensive way.**

Keywords **– Tire Hydroplaning, Coupled Euler-Lagrange, Computational Fluid Dynamics.**

I. Introduction

When the vehicle is running on the wet road, the hydrodynamic pressure generated by water on the road will reduce the contact force and contact area between the tire and the road, affecting the vehicle's braking and handling stability. In serious cases, the tire will be completely off the ground and tire water skiing phenomenon will occur. Therefore, tire hydroplaning is of great significance to vehicle safety.

The research methods of tire hydroplaning are mainly divided into experiment and numerical simulation. In the early stage, experiments and numerical analysis were used to study hydroplaning. The earliest research on the hydroplaning of tires began in the 1960s when Horne et al. [1-3] obtained the empirical formula of the critical hydroplaning velocity of tire inflation pressure through statistical analysis of a large number of test data. However, due to the limitations of experimental results such as test cost, after the rise of computer in the 1990s, a large number of researchers [4-8] used CEL method or CFD method to analyze the tire hydroplaning. Guo et al. [9] studied the influence of lateral slope on tire hydroplaning based on CFD method. In Fluent, Zhou et al. [10] studied the improvement of water-skiing ability of bionic V-shaped grooves and bypass pipes in tire grooves based on CFD method. Ding et al. [11,12] studied the hydroplaning performance of wide-base truck tires and the hydroplaning risks of PFCS multi-lane roads under different rainfall intensity based on CEL method.

The above research indicates that the numerical calculation methods of tire hydroplaning are mainly Coupled Euler-Lagrange (CEL) method and Computational Fluid Dynamics (CFD) method. Researchers generally use one of these methods, cannot fully simulate the hydroplaning process in detail. This paper introduces in detail using CEL method and CFD method of tire water skiing, using two ways of combining the technical route, from a macro and flow field characteristics on the comprehensive analysis of tire hydroplaning, in order to more complete comprehensive analysis of tire hydroplaning, improve the reliability of simulation hydroplaning.

II. The Establishment of Finite Element Model

A. *Tire Model and Road Model*

As the main body of tire water-skiing phenomenon, accurate and effective modeling is the premise of obtaining correct results. The material of 205/55 R16 tire includes rubber and cord. The rubber is described by super-elastic Neo-Hookean model, and the cord is described by rebar unit. Firstly, in Auto CAD, the section structure diagram of tire is cleaned and simplified. Secondly, it is imported into the pre-processing software Hypermesh, and two-dimensional mesh is divided according to the internal structure of the tire. Finally, the two-dimensional mesh is rotated in ABAQUS to generate the three-dimensional finite element model of the tire. In order to save the calculation cost of the model, analytic rigid body is used as the loaded pavement on the premise of not affecting the calculation accuracy, as shown in Fig. 1.

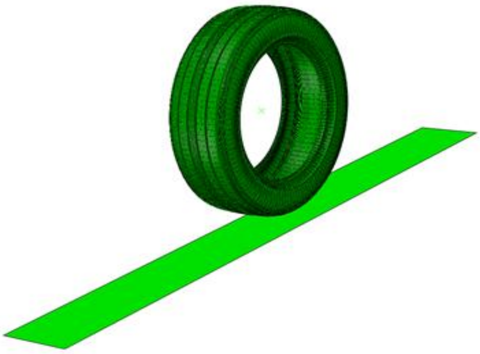
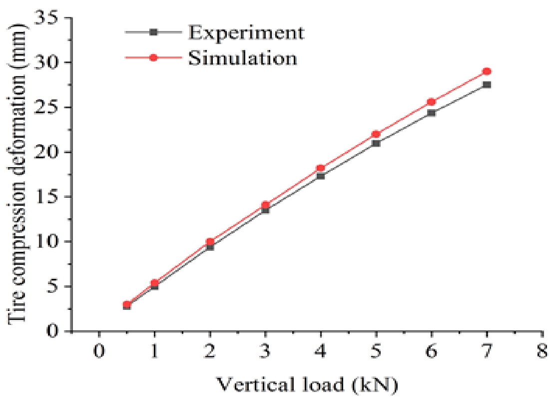


Fig. 1. Finite element model of tire and road.

B. *Model Validation*

In order to verify the accuracy and applicability of the finite element model of tire, CSS-88100 static load testing machine is used to carry out load test on the tested tire, as shown in Fig. 2(a). During the analysis, the tire inflation pressure was 250 kPa and the rated load was 3700 N. The comparison between the test and simulation results of the load-tire compression deformation curve under static loading is shown in Fig. 2(b). The test and simulation error is very small (maximum 3.56%), indicating that the simulation model has high reliability.

(a) CSS-88100 static load testing machine.

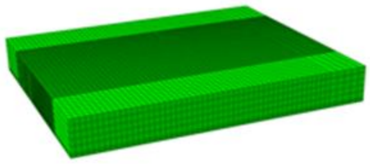


(b) Load-tire compression deformation curve.

Fig. 2. Model Validation.

C. *Establishment of Euler Water Film Model*

There are two main methods to simulate the tire water-skiing phenomenon based on CEL method: water flow impact model and tire rolling model. The water flow impact model is to convert the forward movement of the tire into the backward impact of the water flow on the rotating tire through the transformation of the relative motion coordinate system. The tire rolling model simulates real tire movement through a stationary water film. In ABAQUS/CAE, the water flow impact Euler water film model and the tire rolling Euler water film model are established, as shown in Fig. 3. The lower part of the model is water layer, which is divided into 3 layers of grid, while the upper part is reserved air layer, which is divided into 5 layers of grid. The specific parameters of the model are shown in Table 1.



(a) Flow impact model

(b) Tire rolling model

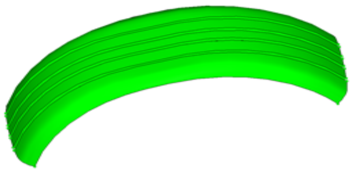
Fig. 3. Euler Water Film Model.

Table 1. Fluid model parameters.

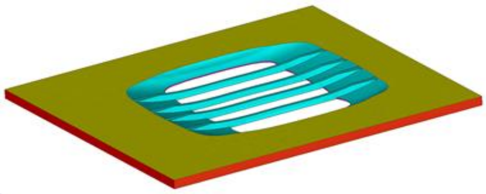
Fluid model	Length/mm	Width/mm	Height/mm	Water layer thickness /mm	Number of Elements
Flow impact model	1000	1000	60	10	561600
Tire rolling model	2000	1000	60	10	520000

D. *Establishment of Fluid Domain Sub Model*

The professional computational fluid dynamics software Fluent was used to analyze the tire hydroplaning from the aspect of flow field characteristics. First of all, tire inflation, loading, steady rolling and other operations are carried out in ABAQUS to obtain steady rolling deformation mesh of tire, which is imported into the Hypermesh. Secondly, the deformation entity model of the tire joint area is generated in the Hypermesh, as shown in Fig. 4(a). Finally, the fluid domain grid is generated, as shown in Fig. 4(b).



(a) Tire joint area deformation solid model.



(b) Fluid domain mesh.

Fig. 4. Fluid domain sub model.

III. BOUNDARY CONDITIONS

A. *Flow Impact Model Boundary Conditions*

The flow impact three-dimensional finite element model of "tire - water - road" based on CEL method is shown in Fig. 5.

(a) Tire: All the degrees of freedom of the rim except the Y-axis rotational and Z-axis translational degrees of freedom are constrained, and the state of stress and strain of steady-state rolling of the tire is introduced. According to different driving speeds, certain angular velocity is applied to the tire.

(b) Water film: Restrict the z-axis velocity at the bottom of Euler region to ensure that the water does not penetrate downward. Set the vertical gravitational acceleration in the Euler region. The front end of Euler model is set as free entrance and a certain flow velocity is set. Set the back end of the model to the outflow boundary.

(c) Road: Constrains all degrees of freedom except X-axis translational degrees of freedom, applying a speed equal to the flow of water.

B. *Tire Rolling Model Boundary Conditions*

The tire rolling three-dimensional finite element model of "tire - water - road" based on CEL method is shown in Fig. 6.

(a) Tire: All degrees of freedom of the rim except X-axis translational freedom, Y-axis rotational freedom and Z-axis translational freedom are constrained, and the state of stress and strain of steady-state rolling of the tire is introduced. According to different driving speeds, certain angular velocity and velocity are applied to the tire.

(b) Water Film: Velocity in the z-axis direction at the bottom of the Euler region is constrained. Set the vertical gravitational acceleration in the Euler region. Constrain the velocity of the wall on both sides of Euler model.

(c) Road: Constrains all degrees of freedom of the road.

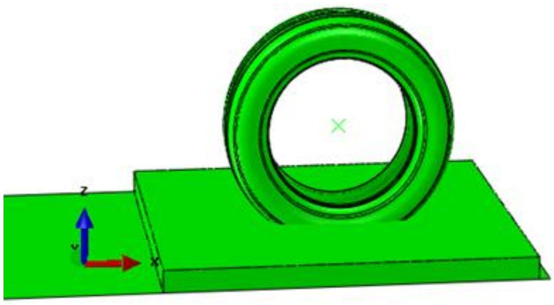


Fig. 5. The flow impact three-dimensional finite element model of “tire - water – road”.

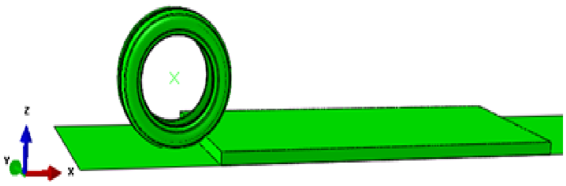


Fig. 6. The tire rolling three-dimensional finite element model of “tire - water – road”.

C. *Fluid Domain Sub Model Boundary Conditions*

(a) Velocity inlet: The front of the model is set as the flow velocity inlet.

(b) Pressure outlet: Set the rear and side of the model as pressure outlet.

(c) Wall: The top of the model is set as a non-movable wall without slip, and the bottom is set as a movable wall without slip.

IV. Results and Discussion

A. *Tire Rolling Model*

Tire accelerates from 20 m/s to 24 m/s on wet roads, as shown in Fig. 7. It can be seen that when the tire is driving on the road, the water flow gathers at the front end of the tire ground, and the dynamic hydraulic force acts as the water lift force for the tire tread. As the velocity increases, the water lift force increases gradually, and the road contact force decreases gradually, as shown in Fig. 8. When the velocity increases to a certain degree, the water lift force is equal to the tire load, the road contact force drops to zero, the tire occurs hydroplaning, at this time the velocity is critical hydroplaning velocity. As the tire travels, most of the water is discharged from the tire side, and a little water enters the longitudinal pattern of the tire. This is also consistent with the actual situation.

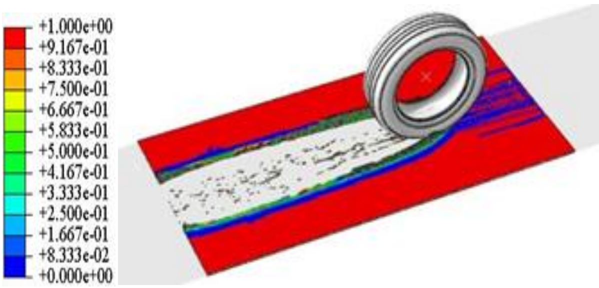


Fig. 7. The water imprint of tire rolling model.

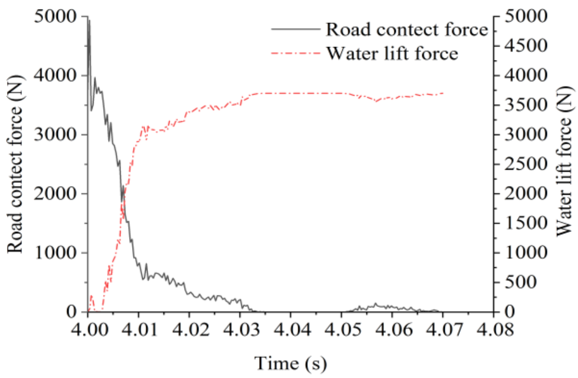


Fig. 8. Road contact force and water lift force.

B. *Flow Impact Model*

Water imprint of the flow impact model with a velocity of 80 km/h is shown in Fig. 9. It can be seen that the motion state of its water flow is similar to that of the tire rolling model. It can be seen that the movement state of water flow is similar to that of tire rolling model. Water flow gathers continuously at the front of tire ground and forms a wedge-shaped water film, most of which is discharged from the tire side. At the same time, the critical hydroplaning velocity of the tire determined by the water impact model is 76.82km /h, and the critical water skiing speed of the tire determined by the rolling model is 78.65km /h. The difference between the critical hydroplaning velocity determined by the two models is 2.33%. It can be seen that the results of the two tire hydroplaning simulation models are very similar. Since the calculation time of the tire rolling model is much longer than that of the water impact model, researchers generally use the water impact model to analyze the tire hydroplaning.

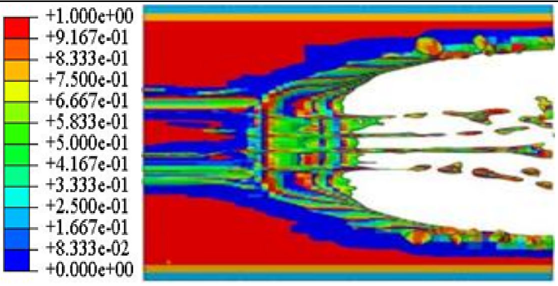
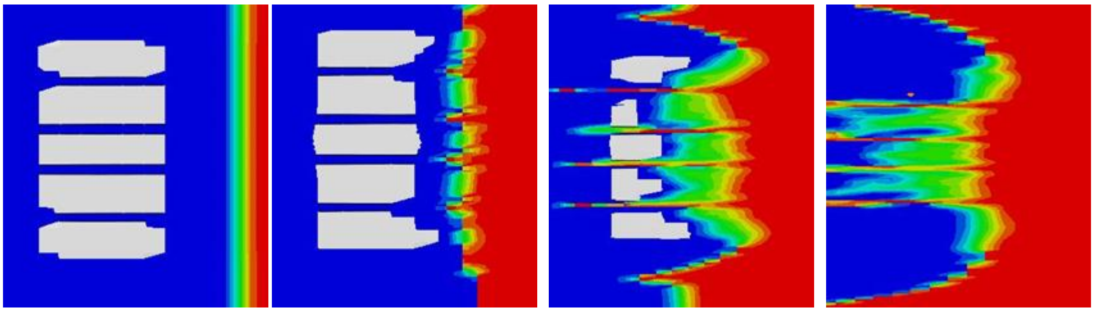


Fig. 9. The water imprint of Flow impact model.

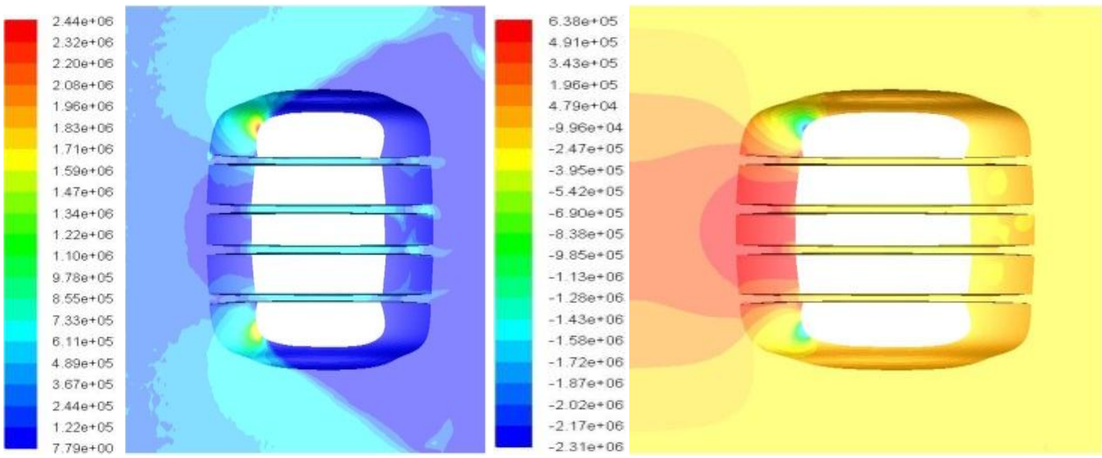
The relationship between tire and road contact imprint with time is shown in Fig. 10. In the figure, the white area is the contact imprint of the tire, and the red area is the water flow. At t = 4.005s, the water has not reached the tire connection area, and the tire contact imprint was close to the rectangle. At t = 4.007 s, the water reached the front of the ground and converged here due to the obstruction of the tire, and the contact area between the tire and the road began to decrease. At t = 4.010 s, the lift force of water flow generated by hydrodynamic pressure began to lift the tire, the water began to invade the tread, part of the water discharged from the tread groove of the tire, and the contact area between the tire and the road was further reduced. At t = 4.025 s, the water flow completely lifts the tire, the contact area between the tire and the road dropped to zero, and the tire water skiing occurred.



t = 4.005 s   t = 4.007 s   t = 4.010 s   t = 4.025 s

Fig. 10. Contact area between tire and road surface.

C. *Flow Impact Model*



(a) Hydrodynamic pressure cloud chart.   (b) Static pressure cloud chart.

Fig. 11. Pressure cloud chart.

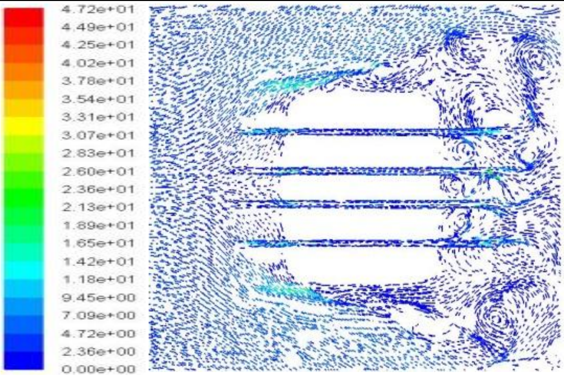


Fig. 12. Flow velocity distribution cloud map.

The hydrodynamic and static pressure of the fluid domain sub model with a velocity of 80 km/h are shown in Fig. 11. As can be seen from Fig. 11(a), the peak hydrodynamic pressure at the tire shoulder on both sides of the tire is large, the maximum value is 2440kPa, and the hydrodynamic pressure at the front end of the tire grounding is small. It can be seen from Fig. 11(b) that the static pressure area of the tire is mainly concentrated at the front end of the tire grounding, and a negative static pressure center is formed at the shoulder of both sides of the tire, and a smaller negative static pressure center is formed at the outlet of the pattern groove. It can also confirm the conclusion of water flow motion obtained above from Fig. 11. The large pressure difference between the earthing front end and the tire shoulder on both sides is the reason for most of the water flow to be discharged from the tire side, while the small pressure difference between the earthing front end and the tire pattern groove outlet leads to only a small part of water flow to be discharged from the pattern groove. In addition, the velocity distribution cloud map of the tire flow field at 80 km/h is shown in Fig. 12. It can be seen that a large number of vortexes of different sizes are distributed at the exit of the pattern groove. These vortices affect the drainage capacity of the longitudinal grooves. One way to improve the water-skiing performance of tires is to reduce the number of eddies at the exit of the pattern groove by optimizing the pattern structure.

V. Conclusion

The rolling model and water flow impact model are established based on CEL method. It is found that the critical hydroplaning velocity of the tire calculated by the two models differs little. Compared with the tire rolling model, the water impact model can greatly shorten the calculation cycle, so the water impact model is used to analyze the tire water hydroplaing in general.

A submodel of the fluid domain is established by using CFD method, and the tire hydroplaning is analyzed based on the flow field characteristics. It is found that the hydrodynamic pressure at the tire shoulder on both sides of the tire is large, there is a large static pressure center at the middle part of the tire earthing front, and the vortex at the outlet of the tread groove affects the drainage capacity of the tread groove.

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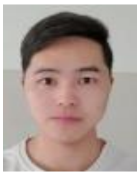

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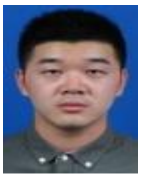

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