Graduate School of Creative Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Space–Time Computational Analysis of Tire Aerodynamics with Actual Geometry, Road Contact, Tire Deformation and Fluid Friction

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A tire is a mechanical part that has numerous functions. These functions are categorized in three main areas: "For life", "For safety", and "For the environment".

“For life” is associated with how comfortable and quiet a tire is. All roads have roughness, so a passenger feels the vibration from the road. The tire absorbs the impact from the road like a cushion making the passenger feel more comfortable. A tire is related to noise, too. The driving noise has mainly 3 types: cavity resonance noise, road noise and pattern noise. When a tire contacts the road, the air surrounded by the groove and the road is vibrated. That causes cavity resonance noise. Road noise is due to the road roughness. Tread pattern noise is caused by the tire tread. When a tire contacts the road, the air surrounded by the groove and the road is compressed as well as the air between the tire and the road. That causes the noise.

“For safety” corresponds to a tire’s stability and drainage property. The tire is the only part that can transpose the forces to the road. Tire plays an important role in turning and breaking. This property is related to the friction forces of the contact area. A tire is covered by rubber. Rubber has viscoelastic property which is very complicated. While driving, the rubber is heated by the tire rotation. This high temperature makes the rubber softer, then the contact area becomes bigger than the initial size. To deliver high friction forces, larger contact area and smaller groove area are needed. On the other hand, fewer groove area causes low wet property. Under high-speed driving conditions, water film causes hydroplaning phenomenon. It makes the tire slippery, and the passenger cannot control the vehicle. To get high wet property, the tread pattern design is important to flow out water film.

“For the environment” is related to reducing fuel consumption which is regulated on a global scale. The amount of CO2 emitted from the vehicle is a deep problem, and a tire’s design is constrained to reduce it. To reduce CO2 relatively, low fuel consumption is required. Rolling resistance is a substantial part of the percentage of vehicle energy loss. Therefore, lower rolling resistance makes the mileage longer and the fuel consumption lower. Generally, the rolling resistance is related to the wet performance. If a tire has low rolling resistance, it makes the wet performance worse. It is a complex problem. A tire has many functions, and the design is required to satisfy many performance tests. Therefore, there is a trade-off among these design requirements. The desired tire should have an overall good performance. At first, we must find out how the air flows around a tire. Considering the tire design, the air is an important factor.

Many companies conduct wind tunnel tests for getting a flow field around a tire. There is a belt under the tire, a driving motion can be represented by moving the belt. The test can get flow field around the tire. However, the representation of the boundary layer phenomenon near the tire surface is limited. The tire has thin boundary layer thickness because of high Reynolds number. In my computations, I assumed 1 m as the tire diameter, and the boundary layer thickness is about 0.1 mm. It would be difficult to capture such a small boundary layer near the tire surface in the wind tunnel test.

Because of this restriction in the wind tunnel tests, the companies want to get more detailed flow field by the computational fluid dynamics (CFD) instead of an experiment. The performance of computers is growing even now. Recently, we can compute even very high-resolution mesh. However, there are specific problems related to

CFD for tire aerodynamics analysis.

It is more accurate to represent the contact between the tire and the road. However, if the analysis is with contact, then the moving boundaries becomes more challenging. Because there requires a mechanism which deals the collapsing the volume due to the contact.

In this thesis, we propose a new method that enables to carry out tire aerodynamics analysis with road contact and tire deformation.

This method has four components, the Space–Time Variational Multiscale (ST-VMS) method, the ST Slip Interface (ST-SI), ST Topology Change (ST-TC) methods and the ST Isogeometric Analysis (ST-IGA). The ST-VMS applies the residual based VMS (RBVMS) to ST method. It is a consistent formulation. The ST-SI allows moving-mesh computations with mesh rotation. The ST-TC enables moving-mesh computations even with the topology changes created by the contact between the tire and the road.

In computation, the tire-road contact is treated by the ST-SI and the ST-TC. There are rotating and stationary domains. The rotating domain includes the boundary representing the tire and SI, which connects to the stationary domain. The stationary domain has the other boundaries including the road and the SI corresponding to the rotating domain. The contact is represented by two collapsing volumes. One is between tire and corresponding SI, another one is between road and corresponding SI. The contact region changes in time. The ST-IGA is an additional method to it. It makes the computation more accurate and efficient because of the correct surface expression, which is based on computer-aided design (CAD). The most popular model of CAD is non-uniform rational B-spline (NURBS). One of the strong points of NURBS is that it can represent cone, cylinder, and sphere exactly. It can also represent smooth surfaces. Near the contact area, elements have high skewness. The NURBS can represent such reason without having many elements.

Solving a simple 2D problem gives us verification of the method. In the problem, there is a cylinder and flat solid surface. A cylinder is spinning and deforming on a solid surface. This is similar to the situation that a tire without grooves contacts to the road. This problem we can represent either prescribed velocity on the rotating surface or actually rotating the domain as explained above. Using prescribed velocity does not need a new method and therefore new method can be compared with established method. Refinement study is also conducted. The refined mesh has two times higher resolution in normal and tangential direction than the preliminary one. With new method, the velocity profile near the boundary is in good agreement with the one with prescribed velocity.

Tire aerodynamics analysis with an actual tire geometry, tire deformation, and road contact is a challenging problem. In the computation a tire geometry, which was designed for examination, is used. It has 3 longitudinal and 72 transverse grooves. A set of deformation patterns is obtained by a finite element analysis, which was provided a tire company. The contact area is defined by the height from the road. From the computation near the contact area high velocity is observed, which is related to the mass balance law. The shear stress of the tire boundary is calculated from the velocity distribution. The shear stress shows that there is large difference between the front of the tire and back of tire.

The global Reynolds number, using tire diameter as reference length, is about 100,000. On the other hand, the local Reynolds number, using the depth of the groove as reference length, is about 10–100. Therefore, this is a multiscale problem.

In the tribology, Reynolds equation is widely used, which is a simplified version of Navier–Stokes equations based on some assumptions. The assumptions of the simplification are as follows. It assumes that two surfaces are very close to each other and the length scale in the flow is much larger than the gap between the surfaces. It gives a low Reynolds number and inertia of the fluid is ignored. It also ignores the curvature of the surface. Such condition problem can be also solved by ST-VMS because the Reynolds equation is the simplified version of Navier–Stokes equations. First, a flow between two cylinders is tested. The second is a computation with tire aerodynamics but assuming that there is a small gap between the tire and road. The results show that ST-VMS can be applied even from very low Reynolds number to high Reynolds number flows.

In conclusion, the method introduced in this thesis enables tire aerodynamics analysis with tire rotation and road contact. NURBS helps representation of narrow space. In addition, one of the core methods, ST-VMS deals with the multiscale problem with a gap near the contact area.

早稲田大学　博士（工学）　学位申請　研究業績書

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Journal Articles (Peer-Reviewed)	○ 1. **T. Kuraishi**, K. Takizawa, and T.E. Tezduyar, "Space–time isogeometric flow analysis with built-in Reynolds-equation limit", *Mathematical Models and Methods in Applied Science*, (**in printing**).
	○ 2. **T. Kuraishi**, K. Takizawa, and T.E. Tezduyar, "Tire aerodynamics with actual tire geometry, road contact and tire deformation", *Computational Mechanics*, (**published online**).
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