HYDROPLANING SIMULATION USING FLUID-STRUCTURE INTERACTION IN LS-DYNA

Masataka Koishi, Toshihiko Okano,*
The Yokohama Rubber Co.,Ltd.

Lars Olovsson,
LSTC

Hideo Saito and Mitsuhiro Makino
Fujitsu Ltd.

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* Corresponding author: koishi@hpt.yrc.co.jp

ABSTRACT

The hydroplaning phenomenon is a key issue for safe driving on a wet road. However, it has been extremely difficult to predict the onset of hydroplaning using numerical simulation. The hydroplaning is a complex multi-physics problem, involving rolling tires with complex groove geometry and surrounding water. Recently the fluid-structure interaction capability has been developed for both Eulerian and ALE formulations in LS-DYNA. Using this capability, transient hydroplaning can be modeled for both the reference frame fixed on a moving car (Eulerian fluid) and the reference frame fixed on the ground (ALE fluid). In the present work, both tire and fluid are modeled with Finite Elements. Numerical examples of the passenger car radial tire sized 195/65R15 with V-shaped grooves are illustrated. In the proposed simulation, we obtain a tire completely lifted by the water layer. In addition, the difference in lifting velocities between normal rotational direction and reverse rotational direction has been evaluated. The numerical results correspond well to the experimental observations at a proving ground.

Key Words : Fluid-structure interaction, Hydroplaning, Tire, Eulerian, ALE

1. Introduction

Tires are important structures to transmit forces and moments between an automobile and road. The basic required functions of tires are:

1. to have load-carrying capacity,
2. to transmit driving and braking torque,
3. to provide cushioning ability,
4. to provide cornering force.

In addition, many other tire functions are required, e.g. to be durable, to provide adequate mileage, to produce minimum noise and vibrations and so on. The hydroplaning phenomenon, that is the focus of this study, is the key issue for safe driving on a wet road among the rest. Numerical simulations are extremely helpful to predict the performance of tires. Simulations can predict the onset of hydroplaning phenomenon they are important and helpful for the designing of the groove geometry of tires. Hydroplaning is the phenomenon where a vehicle drives on a road covered by a water film, in which the frictional force diminishes between tire and the road surface. The phenomenon is caused by a dynamic pressure increase in the water film above the contact pressure of tire and road. It has been extremely difficult to solve the transient hydroplaning phenomenon using numerical techniques such as FEM. Hydroplaning is a highly nonlinear multi-physics problem involving a deformed rolling tire and water with free surfaces. Recently the fluid-structure interaction capability has been developed for both Eulerian and ALE formulations in LS-DYNA [1]. Moreover, LS-DYNA has been enhanced to solve the challenging problem, onset of hydroplaning of tires with complex groove geometry. Using the improved LS-DYNA capabilities, we can solve the transient hydroplaning phenomena based on both reference frame fixed on a moving car (Eulerian formulation) and reference frame fixed on a ground (ALE formulation).

2. Hydroplaning phenomena

Hydroplaning is the phenomena, in which frictional force diminishes between tire and road surface, when a vehicle drives on a wet road covered by water film. The condition of the interface between tire and road during hydroplaning is called mixed lubrication as shown in Fig.1.

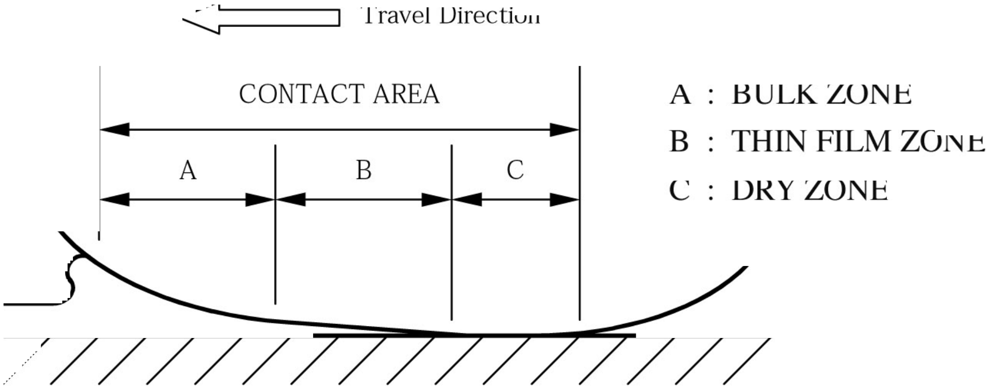


Fig.1: Schematic figure of hydroplaning phenomena [2]

In region A dynamical pressure, due to collision of water and tire, lifts the tire. Region B is a transient zone, in which a thin water layer exists and the tire is partially lifted. In region C, no water film exists and tires adhere to the road completely. When a vehicle drives at low speed, region C dominates the contact patch, in which no water film exists between tire and road. As the vehicle velocity increases, dynamical pressure of water tends to lift the tire and region A becomes dominant.

3. Hydroplaning simulation using LS-DYNA

Many procedures for solving fluid dynamic problems have been implemented in LS-DYNA. This study focuses on Eulerian and ALE formulations. The fluid-structure interaction capability has been developed for both Eulerian and ALE descriptions of motion. The algorithms have been improved to be applicable to hydroplaning simulations. Using the current capabilities, the onset of the hydroplaning phenomenon can be predicted for tires with complex groove geometry.

3.1 FE model of a tire and fluid

We consider a passenger car radial tire sized 195/65R15 with V-shaped grooves. The groove design of the tires should be modeled in the hydroplaning simulation, because it is the most important issue for the hydroplaning performance. On the V-shape grooved tire, the hydroplaning performance depends on the rotational direction. Figure 2 shows an FE model of the simulations of both normal rotation and reverse rotation. A tire is modeled with a Lagrangian mesh of 22,111 elements and the fluid, which contains water domain and void, is modeled with an Eulerian mesh of 86,400 elements. Tires are made of rubber components and fiber reinforcements. The rubber components are modeled with solid elements and the reinforcements are modeled with shell elements. The FE models of the grooves and a tire body are generated independently and connected to each other by a tied contact capability. Using this modeling procedure, groove FE meshes with arbitrary geometry can be generated easily. In addition, groove design is modeled by hexahedral solid elements to accurately predict the contact patch and the pressure distribution.

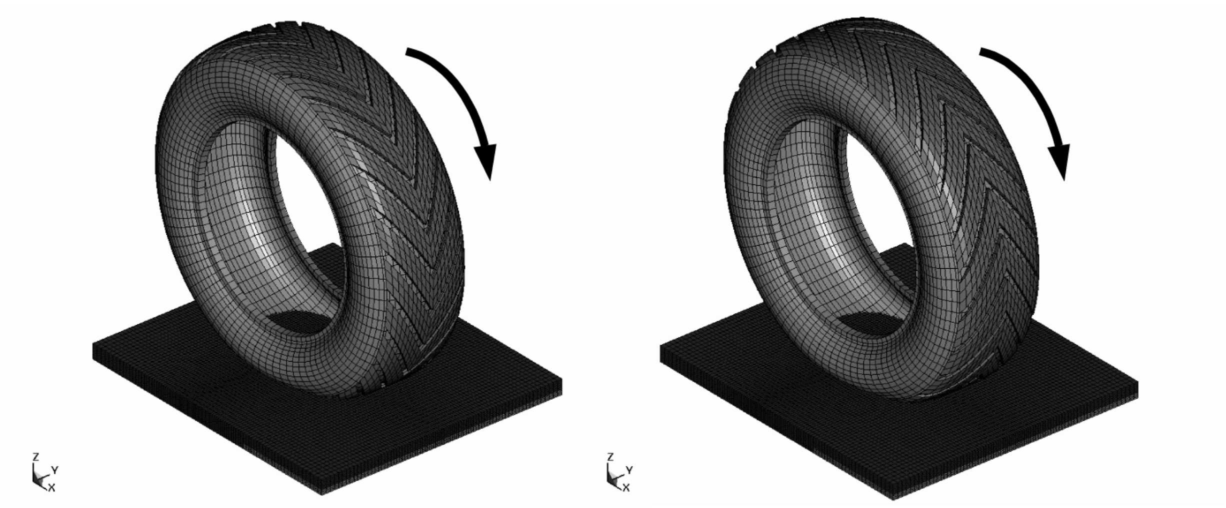


Fig.2: FE model for hydroplaning simulation:
normal rotation model (left) and reverse rotation model (right)

The interface region between a tire and fluid are shown in Fig.3. Thickness of water film and that of void are 10 mm and 20 mm, respectively. The tire FE model is not covered by water elements in order to be applied inflation pressure and vertical load without interaction between water and a tire.

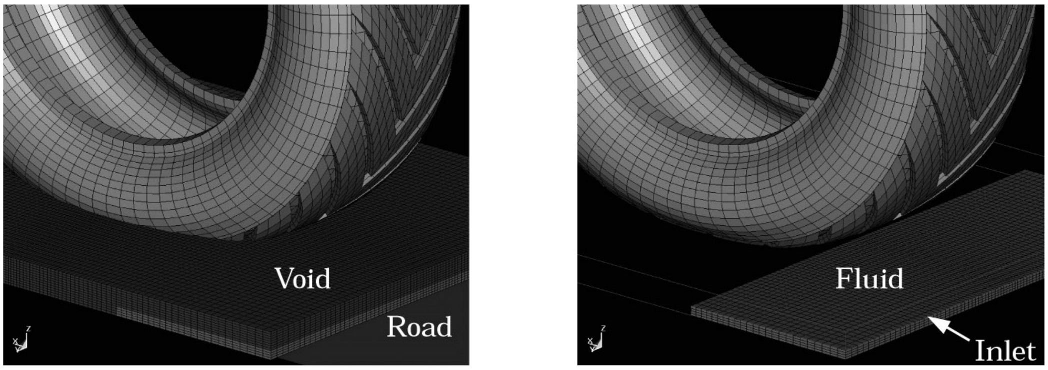


Fig.3: FE modeling of the FSI region

3.2 Fluid-structure interaction in LS-DYNA

Two different formulations are implemented in LS-DYNA for compressible fluid dynamics; one is called multi-material Eulerian and another is multi-material ALE. The multi-material Eulerian formulation is a method where two or more different materials can be mixed within the same fixed mesh. Each element in the Eulerian mesh contains a certain volume fraction of each material. To reduce the mass flux, ALE techniques can be incorporated in the multi-material formulation. The multi-material ALE mesh is given a prescribed motion, which somehow follows the motion of the material inside the mesh. The mass flux can, in some applications, be kept smaller than with a pure Eulerian formulation. In addition, the ALE model can sometimes be made smaller, as only the current domain of interest needs to be enclosed by the multi-material mesh. The hydroplaning model contains a special case of material combinations, single material and void.

A special coupling algorithm is required for the interaction between an Eulerian fluid and a tire with complex geometry of grooves. In this context, a penalty-based Lagrangian-Eulerian coupling algorithm was developed, aiming at energy conservation and at a straightforward treatment of friction.

The governing equations in conservation form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, \mathbf{v}) = 0$$

$$\frac{\partial \rho\, \mathbf{v}}{\partial t} + \nabla \cdot (\rho\, \mathbf{v} \otimes \mathbf{v}) = \nabla \cdot \boldsymbol{\sigma} + \rho\, \mathbf{b}$$

$$\frac{\partial \rho\, e}{\partial t} + \nabla \cdot (\rho\, e\mathbf{v}) = \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}} + \rho\, \mathbf{b} \cdot \mathbf{v}$$

A transport term complicates the treatment of the governing equations. A convenient way to numerically deal with the systems of equations is to use an operator split method, in which the evolution of the solution variables is divided into a few steps:

1. Lagrangian step

$$\mathbf{v}^{n+1/2} = \mathbf{v}^{n-1/2} + \Delta t\, \mathbf{M}^{-1} \left\{ \mathbf{F} - \int \mathbf{B}^{T} \boldsymbol{\sigma}\, d\Omega \right\}$$

$$\mathbf{x}^{n+1} = \mathbf{x}^{n} + \Delta t \mathbf{v}^{n+1/2}$$

2. Mesh smoothing

   Eulerian : Mesh is returned to original configuration
   ALE : Mesh is moved to a prescribed manner

3. Advection phase

   Donor cell scheme or Van Leer scheme for history variables
   Interface reconstruction for volume fractions

4. Mixture theory

   Volume fraction weighted stress

5. go to “Lagrangian step”

3.3 Procedure of hydroplaning simulation

One can choose different reference frames for a hydroplaning simulation. The hydroplaning can be modeled as a rotating tire moving on a fixed road covered with water. However, such an approach necessarily needs a fine mesh over the entire region of water, in which the tire is expected to roll, leading to an impractical size of number of elements. As mentioned before, the multi-material ALE formulation is useful for such situations. Another possible approach is based on a reference frame fixed on the moving car. The multi-material Eulerian formulation can be used for this situation.

Moreover, in order to reduce the CPU costs, a two step procedure is conducted for the simulations. In the first step, the tire model is subjected to an inflation pressure of 200kPa and a vertical load of 4kN. In this first step there are no fluid elements. The second step is a restart run from previous step. In this step, the relative velocity between the tire and the road is increased from 0km/h to 120km/h, under constant acceleration. The history of reaction forces between the tire and the road can be obtained.

3.4 Numerical results

Figure 4 represents the predicted contact force variations between a tire and road, when the V-shape grooved tire rotates. Contact forces decrease, as the relative velocitiy between the tire and the fluid mesh increase. Contact force for the reverse rotation diminishes to zero at lower velocity than the normal rotation, which indicates that the tire is completely lifted above the water layer. These results correspond well to experimental results on the proving ground. Results from the multi-material Eulerian formulation and the multi-material ALE formulation show the same tendency.

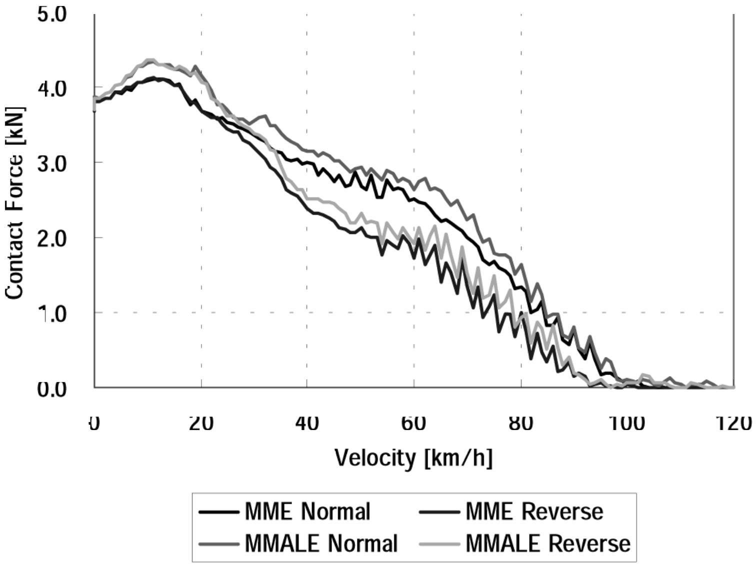


Fig.4: Contact forces between a tire and road

The computed free surface and material boundary are shown in Fig.5. The left figure shows results from a normal rotational simulation, at 75km/h. The right figure shows results from reverse tire rotation at the same velocity. When a V-shaped grooved tire rotates in reverse direction, a water wedge intrudes into the tire contact patch and the contact area is reduced.

Figure 6 shows the intrusion process with a water wedge lifting the tire, as the velocity increases. Simulation results indicate that the water wedge intrudes into the contact patch gradually, as fluid velocity increases. The contact patch is completely covered with water when the velocity reaches 120 km/h.

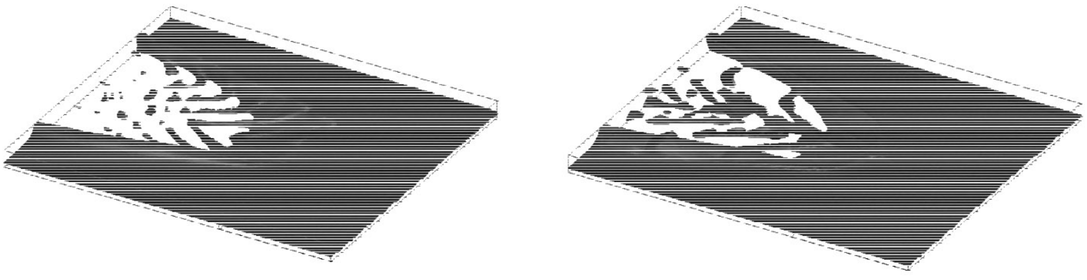
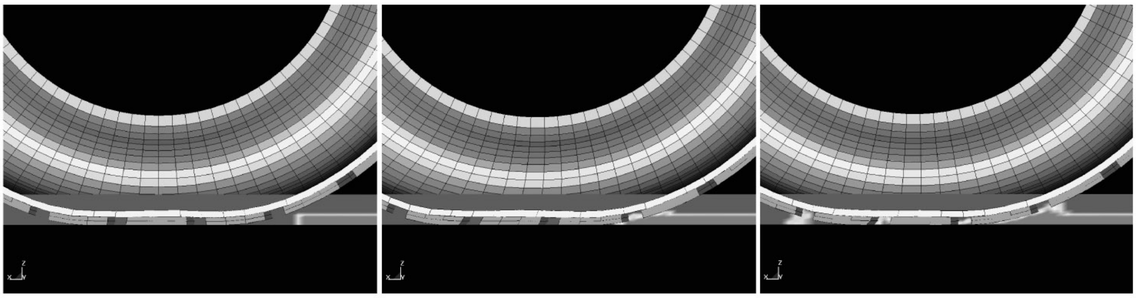
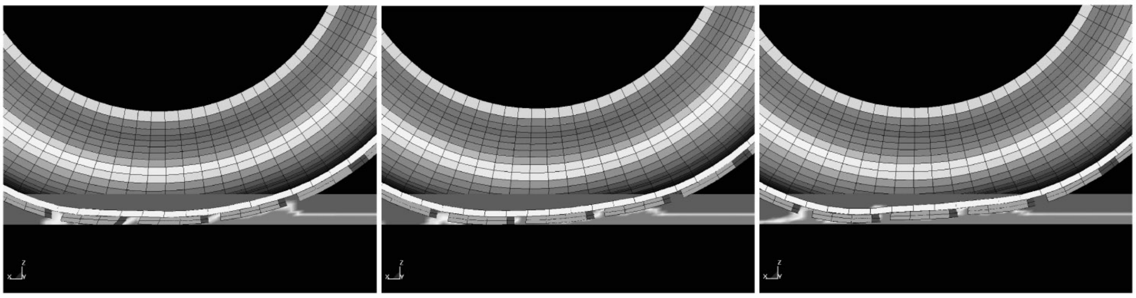


Fig.5 Free surface and material boundary of water:
normal rotation (left figure) and reverse rotation (right figure) at 75km/h



0 km/h 15 km/h 35 km/h



55 km/h 75 km/h 95 km/h

Fig. 6: Intrusion process of water

4. Summary

LS-DYNA has been enhanced to solve the challenging problem, onset of hydroplaning of tires with complex groove geometry. Hydroplaning simulations for both the reference frames fixed on a moving tire (Eulerian fluid) and fixed on the ground (ALE fluid) are demonstrated. The effectiveness of the proposed simulation is displayed, comparing the numerical results and experimental observations on a proving ground. In addition, the penalty based coupling algorithm is found to be robust and useful for hydroplaning simulations.

Reference

[1] Olovsson, L. and Souli, M., ALE and Fluid-Structure Interaction Capability in LS-DYNA, Proceedings of 6th International LS-DYNA Users Conference, (2000).

[2] Allbert, B. J., Tires and Hydroplaning, SAE 680140, (1968).