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Hydroplaning simulation for a straight-grooved tire by using FDM, FEM and an asymptotic method

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Abstract

Much research has been conducted to simulate the hydroplaning phenomenon of tires by using commercial explicit FEM (finite element method) codes such as MSC.Dytran and LS-DYNA. However, it takes a long time to finish such a simulation because its model has a great number of Lagrangian and Eulerian elements, and a contact should be defined between the two different types of elements. The simulation results of the lift force and the contact force are very oscillatory. Thus, in this study a new methodology was proposed for the hydroplaning simulation by using two separate mathematical models. An FDM (finite difference method) code was developed to solve Navier-Stokes and continuity equations and to obtain the pressure distribution around a tire with the inertial and viscous effects of water taken into account. An FE tire model was used to obtain the deformed shape of the tire due to the vertical load and the pressure distribution. The two models were iteratively used until a converged pressure distribution was obtained. Since the converged pressure distribution could not be obtained near or at the contact zone due to very shallow water, an asymptotic method was also proposed to estimate the pressure distribution. This new simulation methodology was applied to a straight-grooved tire, and its hydroplaning speed was finally determined for a water depth of 5 *mm*, 10 *mm*, 15 *mm* and 20 *mm*. Moreover, a new simulation methodology using LS-DYNA was proposed, and the two methodologies were compared in terms of accuracy and efficiency.

Keywords: Hydroplaning; FDM; FEM; Asymptotic method; Navier-stokes equation; Continuity equation

1. Introduction

When an automobile moves on a road with deep water at a high speed, the tires may float due to water pressure built around the tires, causing the automobile to skid. Traditionally, the loss of the traction due to the floatation of tires or the lift force was experimentally measured to determine the hydroplaning speed. In some experimental studies, photos through a glass plate were taken to provide visual images of tire contact shape in water [1]. However, these experimental approaches need tire manufacturing and a test set-up, which entails a comparatively long time and large amount of money. Thus, analytical research on the hydroplaning phenomenon of tires has also been carried out. Saal relied on two-dimensional lubrication theories to predict the hydroplaning speed with no consideration of the inertial effect of water [2]. Martin developed an analytical method to take into account the inertial effect of water only, ignoring the viscous effect of water and the side flow [3]. Eshel divided the tire-water contact area into three zones based on the amount of the inertial and viscous effects, and utilized a different method for each zone [4]. He also considered the overflow at the leading edge although the side flow, but the viscous effect were not taken into account. In addition, Grogger and Weiss introduced a computational simulation for a hydroplaning analysis [5]. Nakajima et al., Okano and Koishi used DYTRAN, a commercial FEM code, to simulate

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hydroplaning of a tire only for over 10 *mm* of water depth because DYTRAN could not handle the viscous effect, which may be significant below 10 *mm* of water depth [6, 7]. Thus, Koishi et al. used LS-DYNA, another commercial FEM code, to simulate hydroplaning of a tire with consideration of the viscous effect as well [8]. However, a great number of Lagrangian elements for a tire as well as Eulerian elements for water around the tire were needed in the simulation, and a significant amount of computing time was used.

Therefore, in this study an FDM code was developed based on the mathematical formulations of Browne to obtain the pressure distribution due to the water flow around a tire [9], and an FE model of a tire was used to obtain the deformed shape of the tire. The deformed tire shape was used in the FDM code to obtain the pressure distribution. The pressure distribution was applied to the FE model to update the deformed shape, which was again used in the FDM code to update the pressure distribution. Through this iterative process, a converged pressure distribution and consequent lift force were determined for a speed. Note that the mathematical formulations in FDM become very ill-conditioned near or at the contact zone where water is very shallow, and consequently the pressure distribution does not converge. Thus, an asymptotic method was also proposed; the lift forces for higher water depths were obtained first, and the lift force for a very shallow water depth was obtained by extrapolating the lift forces for higher water depths. This extrapolation, i.e., asymptotic method, was feasible because the lift forces for higher water depths could be well represented by a simple function. Then, the lift forces were determined for various tire speeds, and the hydroplaning speed could be determined by comparing the lift forces with a critical load. Note that this study used FDM and an asymptotic method to obtain the pressure distribution, whereas other simulation studies [6-8] used FVM.

Moreover, a new simulation methodology using an explicit FEM code such as LS-DYNA was proposed to reduce the CPU time. Instead of a tire rolling over standing water, a tire was modeled to roll at a fixed location, and water was modeled to flow into the tire. In this way, the number of Eulerian elements could be reduced, and consequently the CPU time could be reduced as well. Finally, the simulation results of the hydroplaning speed obtained from the iterative method using FDM and FEM or from LS-DYNA were compared, and these two different simulation methods were also compared in terms of the CPU time and the accuracy.

2. Methodology using FDM and FEM

2.1 FDM

An FDM code was developed based on the mathematical formulations of Browne [9, 10]. Browne assumed the hydroplaning phenomenon to be two dimensional because any variation along the thickness direction was negligible compared with that along the longitudinal or lateral direction, and he used RANS (Reynolds Averaged Navier-Stokes) equations to consider the effect of turbulence. In addition, he used an average of a longitudinal or lateral speed which was represented as a second-order polynomial function through thickness, and defined a stream function by which the continuity equation was automatically satisfied. The governing equations are given as follows.

$$\frac{\partial}{\partial x}\left[\frac{\psi_y^2}{\rho h}\right]-\frac{\partial}{\partial y}\left[\frac{\psi_x\psi_y}{\rho h}\right]+\frac{\mu\psi_y}{G_x\rho h^2}+h\frac{\partial P}{\partial x}=0 \quad (1)$$

$$\frac{\partial}{\partial y}\left[\frac{\psi_x^2}{\rho h}\right]-\frac{\partial}{\partial x}\left[\frac{\psi_x\psi_y}{\rho h}\right]-\frac{\mu\psi_x}{G_y\rho h^2}-\frac{\mu U}{2G_y h}+h\frac{\partial P}{\partial y}=0 \quad (2)$$

Moreover, he used the no-slip condition on the tire and road surfaces, and prescribed zero pressure at the sides and the trailing edge except at the leading edge for which the pressure was calculated from Bernoulli’s equation to consider the effect of a bow wave. He also prescribed the stream function to be zero at the center line since there was no transverse flow in case of a symmetric tire. Finally, he linearized the governing equations by using the Newton-Raphson method, and solved the equations by using the columnwise influence coefficient method. The columnwise influence coefficient method was proved to be efficient in the analysis of gas bearing problems [11].

Note that only a steady state solution can be obtained by using the FDM. That is, the road surface should be smooth, and the pattern of a tire should be the same along the circumferential direction or a tire should be locked up. Thus, in this study the hydroplaning phenomenon of a straight-grooved tire

(P205/45R16) with four grooves of 9.9 *mm* width on a wet road covered with a water depth of 5 *mm*, 10 *mm*, 15 *mm* or 20 *mm* was analyzed. The FDM mesh had about 900 nodes, and the FE tire model had about 35,000 nodes and 41,000 elements. However, the simulation method developed in this study is also applicable to a rotating tire with general tread patterns that are not the same along the circumferential direction; the simulation results will be published in the near future.

2.2 FEM and iterative method

Although the deformation of a tire affects the hydroplaning speed, Browne did not consider it [9]. However, in this study an FEM simulation was incorporated with the FDM simulation in order to consider both the deformation of a tire and the pressure distribution due to water flow. First, an FEM simulation was conducted to obtain the deformed shape of a tire with consideration of the vertical load only. Then, the FDM code was run for the deformed shape of the tire, and the pressure distribution of water was obtained. This pressure distribution was applied to the FE tire model along with the vertical load, and a new deformed shape of the tire was obtained. The FDM code was run again for the new deformed shape of the tire to obtain a new pressure distribution of water. This iterative process was continued until a converged pressure distribution was obtained, and the lift force was calculated from the converged pressure distribution. The lift force was obtained in the same way not only for one speed but also for other speeds, and the lift force could be shown as a function of the speed. This simulation methodology is shown in Fig. 1.

2.3 Asymptotic method

The water depth, h, is in the denominators in the governing equations, Eq. (1) and (2). Consequently,

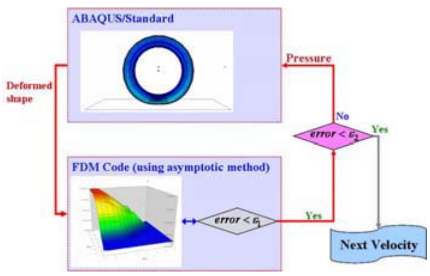

Fig. 1. Schematic diagram of the iterative method.

the linearized matrix equations obtained from the governing equations become very ill-conditioned around the contact zone because of very shallow water, and the pressure there hardly converges. In other words, it is almost impossible to obtain a converged pressure distribution around the contact zone. Thus, an asymptotic method was proposed in this study. The lift force (or the pressure distribution) was obtained with an assumption of water depth being much more than an actual depth; the lift force was obtained as the water depth decreased to a certain value that was still high enough to result in a converged solution. The lift forces for several water depths and speeds shown in Fig. 2 indicated that it was possible to represent the lift force as a function of the actual water depth, the speed and the additional water depth as in Eq. (3). In addition, the numerator could be represented as an exponential function of the actual water depth and the speed as in Eq. (4).

$$lift\ force = \frac{f}{h+H} \tag{3}$$

$$f = c\,h^a\,v^b \tag{4}$$

By using the least square method, the coefficients a, b and c could be readily determined, and they turned out to be 1.25, 2.0 and 0.000115. Note that the exponential function of the speed and the water depth well represents the coefficient f as shown in Fig. 3 and 4 where the symbols represent the coefficient f determined from the lift force which was obtained from the asymptotic method and Eq. (3), and the curves represent the coefficient f obtained from Eq. (4).

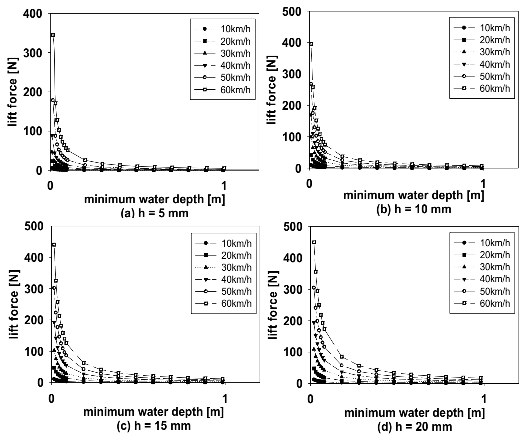

Fig. 2. Lift forces for several water depths and speeds.

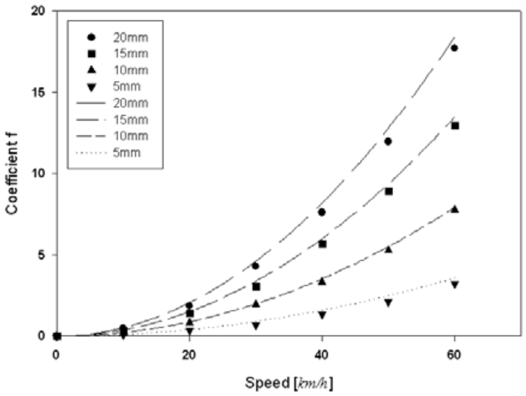

Fig. 3. Coefficient *f* as a function of speed.

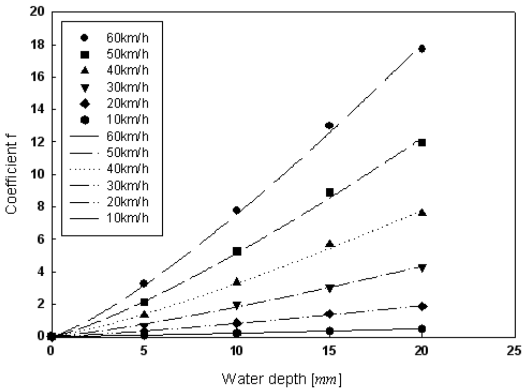

Fig. 4. Coefficient *f* as a function of water depth.

2.4 Simulation results

The vehicle speed and the water depth were proven to play a key role in the hydroplaning phenomenon of a tire [12]. There are several definitions of the hydroplaning speed. First, it is the speed for which the net traction force becomes zero. That is, a vehicle is accelerated over a wet road, and the speed at which the acceleration becomes zero is determined as the hydroplaning speed. Second, it is the speed for which the contact force drops to a certain level, e.g., a half. Third, it is the speed for which the slip ratio reaches a certain value, e.g., 10 %. The hydroplaning speed may become slightly different depending on a definition of the hydroplaning speed. In this study, the first definition was used. Since the net traction force is the friction force subtracted by the air resistance, the rolling resistance and the water drag force, and the friction force is equal to the coefficient of friction times the contact force (i.e., the vertical load subtracted by the lift force), the lift force at the hydroplaning speed

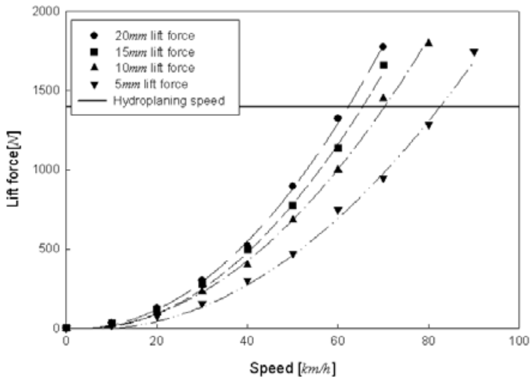

Fig. 5. Lift force as function of water depth and speed.

Table 1. Hydroplaning speed.

	5*mm*	10*mm*	15*mm*	20*mm*
Hydroplaning speed [*km/h*]	82.2	70.3	65.2	62.2

can be represented as Eq. (5). The air drag coefficient, the rolling resistance coefficient and the coefficient of friction were assumed to be 0.3, 0.015, 0.48, respectively [13, 14]. In addition, the drag force calculated from the water pressure around a speed of 64 *km/h* was about 350 *N*. Thus, the lift force at the hydroplaning speed was assumed to be about 1400 *N*, which was 37.2 % of the vertical load.

$$lift\ force = vertical\ load - \left(\mathrm{AR} + \mathrm{RR} + \mathrm{DF}\right)/\mu \cong 1400N \quad (5)$$

The lift force was obtained by using the iterative method and the asymptotic method; it is shown in Fig. 5 as a function of the vehicle speed for several water depths. The symbols are the lift forces obtained from the simulations, and the lines are fitting curves. The simulation result of lift force seems to be qualitatively correct because it increases as the vehicle speed or the water depth increases. The hydroplaning speed was readily determined as the speed at which the lift force became equal to 1400 *N* (Table 1).

3. Methodology using LS-DYNA

A tire and a water film were to be modeled differently to simulate the hydroplaning phenomenon of a tire by using LS-DYNA. A tire was modeled by FEM with Lagrangian elements, but a water film was modeled by FVM (Finite Volume Method) with Eulerian elements. A coupling function was needed to transfer the forces between the two kinds of elements. Recently, fluid-structure interaction capability has been developed for both Eulerian and ALE (Arbitrary Lagrangian Eulerian) formulation in LS-DYNA [15]. On top of the Eulerian elements of a water film, another layer of Eulerian elements was created as "void elements" through which water could splash. The schematic diagram for an LS-DYNA hydroplaning simulation model is shown in Fig. 6.

In the simulation, first, the inflation pressure was applied; second, the vertical load was applied; and finally the tire was accelerated continuously. The total number of elements was about 70,000, and the time increment was about 1×10^{-6} *sec*. Thus, the inflation pressure, vertical load and speed were applied for unrealistically short periods of time as shown in Fig. 7 in order to reduce the CPU time. Even with these unrealistically fast loading and speed conditions, a simulation took over 24 hours in a computer which had 3 *GHz* CPU speed and 3 *GB* memory.

Many researchers have conducted FE hydroplaning simulations in which a tire is rolling forward until its speed goes over the hydroplaning speed [6, 12, 16]. In this case, the number of Eulerian elements became huge requiring a long CPU time because a tire model should roll for a certain distance over which two layers of Eulerian elements should cover. This simulation model is named "a tire rolling model" in this study. Instead of a tire rolling over standing water, a tire was modeled to roll at a fixed location, and water was modeled to flow into the tire. In this way, the number of Eulerian elements could be reduced, and consequently the CPU time could be reduced as well. This model is named "a water flow model" in this study, and the two models are shown in Fig. 8.

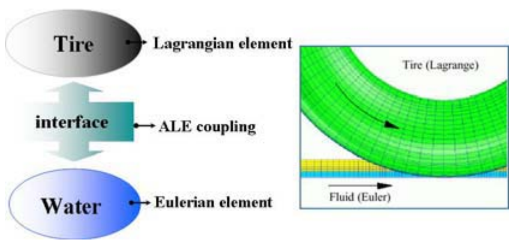

Fig. 6. Simulation by using LS-DYNA.

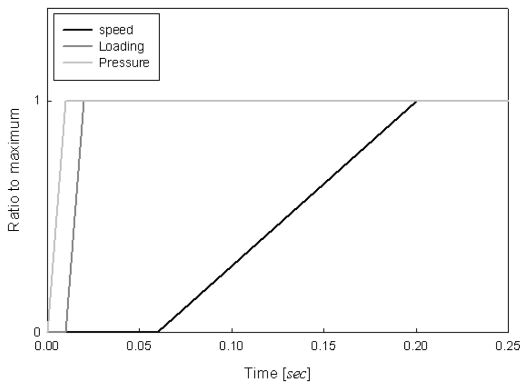

Fig. 7. Loading and speed time histories.

A straight-grooved tire moving on water depth of 10 *mm* was simulated by using the tire rolling model and the water flow model, and the contact force is shown in Fig. 9. It is noteworthy that the results from two models are similar, but CPU time for the water flow model was about 8 hours, which is about four times less than that for the tire rolling model. In addition, note that the contact force, which is the vertical load subtracted by the lift force, is oscillatory. This oscillatory contact force or lift force was also obtained from other hydroplaning simulations by using DYTRAN or LS-DYNA (Nakajima, 2000; Okano, 2001; Koishi, 2001).

4. Comparison of two methodologies

The contact pressure distribution and displacement of two FE tire models, i.e., an ABAQUS tire model used in the iterative method and an LS-DYNA tire model used in the LS-DYNA simulation, were com-

Fig. 8. Tire rolling and water flow models.

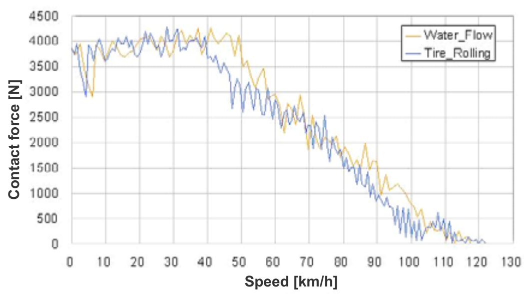

Fig. 9. Contact forces versus speed.

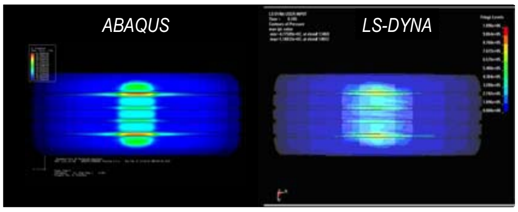

Fig. 10. FE tire models.

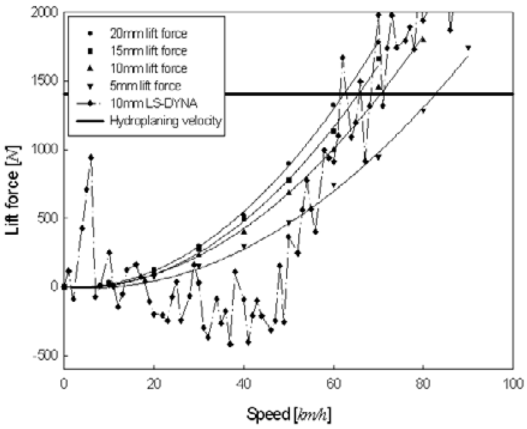

Fig. 11. Comparison of the lift forces.

pared to check whether the models deformed similarly after the inflation pressure and the vertical load were applied. As shown in Fig. 10, the contact pressure from two models looked similar with the maximum pressure being 1.069×10^6 *Pa* and 1.096×10^6 *Pa* under the vertical load of 3767 *N*. In addition, the bead displaced 0.336 *m* in the ABAQUS model, whereas it displaced 0.338 *m* in the LS-DYNA model. Thus, it could be said that the two tire models were compatible and deformed similarly.

The lift forces for water depth of 5 *mm*, 10 *mm*, 15 *mm* and 20 *mm* obtained from the iterative method are shown in Fig. 11 along with the lift force for the water depth of only 10 *mm* obtained from the LS-DYNA simulation by using the water flow model. Even though the iterative method resulted in a smoothly increasing lift force for higher speeds, LS-DYNA resulted in an oscillatory lift force. This oscillation stemmed not only from the characteristic of the explicit FE scheme LS-DYNA relies on but also from the rapid application of loading and speed conditions. The high lift force occurring around 5 *km/h* and the negative lift force occurring around 20-50 *km/h* definitely resulted from the rapid application of the inflation pressure, vertical load and speed. The negative lift force was also obtained from a DYTRAN simulation [7]. The oscillation amplitude was big enough to wash out the effect of water depth or speed on the lift force. This oscillation could have been reduced if the loading had been applied for a longer period of time, but CPU time would have increased almost proportionally.

The CPU time is one of the most important factors in a hydroplaning simulation. The CPU time was about 3 to 4 hours in the case of the iterative method, but it was about 8 hours (or over 24 hours) in case of the water flow model (or the tire rolling model) using LS-DYNA.

5. Conclusions

In this study, a new methodology for the hydroplaning simulation of a tire was proposed. In order to consider the deformation of a tire not only due to the vertical load but also due to the water pressure, an FE tire model was incorporated with an FDM model. They were iteratively used until a converged water pressure distribution was obtained. In addition, in order to obtain the water pressure around the contact zone where water was very shallow, an asymptotic method was proposed. This new simulation methodology was applied to a straight-grooved tire, and the hydroplaning speed was determined. The hydroplaning speed (or the lift force) monotonically increased as the vehicle speed or the water depth increased.

Moreover, another methodology was proposed for a full FEM hydroplaning simulation by using a commercial code such as LS-DYNA. Instead of a tire rolling over standing water, a tire was modeled to roll at a fixed location, and water was modeled to flow into the tire. This water flow model resulted in a similar lift force as the tire rolling model, but it was more efficient, requiring about four times less CPU time. However, unlike the iterative method, the LS-DYNA simulation resulted in such an oscillatory lift force that the hydroplaning speed could vary significantly. In addition, the CPU time of using even the water flow model was over two times that of using the iterative method.

In the near future, a more efficient iterative method which needs only one iteration at each speed to predict the hydroplaning speed will be developed, and the iterative method will be also applied to tires with normal tread patterns.

Nomenclature

Ψ : Stream function
Ψ_x , Ψ_y : Partial derivative of Ψ with respect to the lateral and longitudinal directions
ρ : Density
h : Water depth
H : Additional water depth
v : Vehicle speed
a, b, c : Constants in the asymptotic solution for the lift force
μ : Viscosity
P : Pressure
G_x , G_y : Parameters to account for the turbulence effect

References

[1] T. Suzuki and T. Fujikawa, Improvement of hydroplaning performance based on water flow around tires, Japan Automobile Research Institute (2001).

[2] R. N. J. Saal, Laboratory investigation into the slipperiness of roads, *Chemistry and Industry* 55 (1936) 3-7.

[3] C. S. Martin, Hydrodynamics of tire hydroplaning, Final Report, Project B-608, Georgia Institute of Technology (1966).

[4] A. Eshel, A study of tires on a wet runway, Ampex Corp., RR 67-24 (1967).

[5] H. Grogger and M. Weiss, Calculation of the three-dimensional free surface flow around an automobile tire, *Tire Science and Technology* TSTCA 24 (1) (1996) 39-49.

[6] Y. Nakajima, E. Seta, T. Kamegawa and H. Ogawa, Hydroplaning analysis by FEM and FVM : Effect of tire rolling and tire pattern on hydroplaning *International Journal of Automotive Technology* 1 (2000) 26-34.

[7] T. Okano and M. Koishi, A new computational procedure to predict transient hydroplaning performance of a tire, *Tire Science and Technology* TSTCA 29 (1) (2001) 2-22.

[8] M. Koishi, T. Okano, L. Olovsson, H. Saito and M. Makino, Hydroplaning Simulation Using Fluid-Structure Interaction in LS-DYNA, The 3rd European LS-DYNA Users Conference (2001).

[9] A. L. Browne, Tire deformation during dynamic hydroplaning, *Tire Science and Technology* TSTCA 3 (1) (1975) 16-28.

[10] A. L. Browne and D. Whicker, An interactive tire-fluid model for dynamic hydroplaning, ASTM (1983) 130-150.

[11] V. Castelli and J. Pirvics, Review of numerical methods in gas bearing film analysis, *Transactions of the ASME* (1968) 777-792.

[12] R. S. Huebner, J. R. Reed and J. J. Henry, Criteria for predicting hydroplaning potential, *Journal of Transportation Engineering* 112 (5) (1986) 549-553.

[13] F. M. White, Fluid Mechanics, 4th Ed., McGraw-Hill (1999).

[14] T. D. Gillespie, Fundamentals of vehicle dynamics, SAE (1999).

[15] L. Olovsson and M. Souli, ALE and fluid-structure interaction capability in LS-DYNA, Proceedings of 6th International LS-DYNA Users Conference (2000)

[16] I. Janajreh, A. Rezgui and V. Estenne, Tire tread pattern analysis for ultimate performance of hydroplaning, Conference on Computational Fluid and Solid Mechanics, (2001) 264-267.