Damage Estimation of Vehicle through Tsunami Simulation using Particleworks and LS-DYNA

Particleworks is a Particle Method Based CFD Software developed by Prometech Software Inc. Japan

In recent years, various particle methods have been developed as numerical simulation techniques and used in product design and development. The particle method provides some advantages which can be summarized as follows:

(1) Complex spatial mesh generation is not necessary.
(2) Special treatment to track free surface motion is not necessary.
(3) No mesh distortion in the case of large deformation.

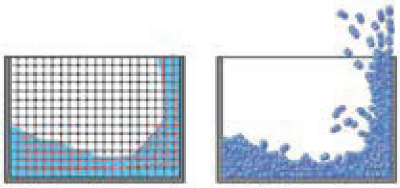

Fig.1 - Schematic images of numerical method

Since the particle method is fully Lagrangian, the advection term can be omitted in the governing equation. Hence numerical diffusion coming from the advection term treatment can be eliminated through the computation. A unique particle method called MPS has been developed and used in various CAE application problems. MPS was originally developed as a discretization scheme of incompressible viscous flow and the first paper dedicated to MPS was published in 1996[1]. The original MPS adopted a semi-implicit time integration scheme, and the abbreviation MPS stands for "Moving Particle Semi-implicit" method. In the meantime, also a fully explicit version of MPS has been developed. Today, MPS is known as a "Moving Particle Simulation" method. MPS is a suitable numerical procedure for the simulation of ordinary incompressible flow, it is applied in particular for different fluid flow problems in the engineering field. In this article, an efficient one-way coupling technique to estimate deformation of products using the MPS-based CFD software Particleworks and the explicit FEM software LS-DYNA is presented. The numerical procedure of MPS is also discussed briefly.

[1] Koshizuka, S. and Oka, Y., Moving-Particle Semi-implicit Method for Fragmentation of Incompressible Fluid, Nucl. Sci. Eng., 123, 421-434, 1996

An efficient technique to treat Fluid Structure Interaction problems

FSI problems need to be solved very often in industrial product design and development. LS-DYNA offers capabilities for modeling FSI problems using SPH (Smoothed Particle Hydrodynamics) or ALE (Arbitrary Lagrangian Eulerian) methods. However, computation of FSI problems with SPH or ALE is very time consuming because a compressible flow solver needs to be used in an explicit time integration scheme with very small time steps. In contrast, MPS, as an incompressible flow solver, can take larger time steps and treat the fluid region very efficiently. Thus a combination of Particleworks and LS-DYNA may be a practical solution to treat the FSI problem. The application example using Particleworks and LS-DYNA presented here is a tsunami simulation of a vehicle. The purpose is the damage estimation of a vehicle drifted by tsunami. If passengers can escape from the drifted vehicle by opening the doors, more people may survive the disaster. A safer design to protect passengers from the impact of a tsunami may be realized. In this context, the suggested procedure of the simulation is as follows:

(1) Perform tsunami simulation using Particleworks in the first phase

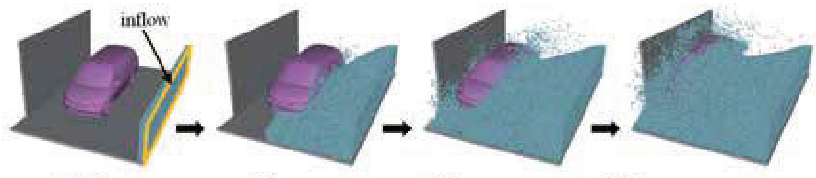

Fig.2 - Results of tsunami simulation using Particleworks

Fig.3 - Example of mapping results of pressure distribution at time = 0.85 sec.

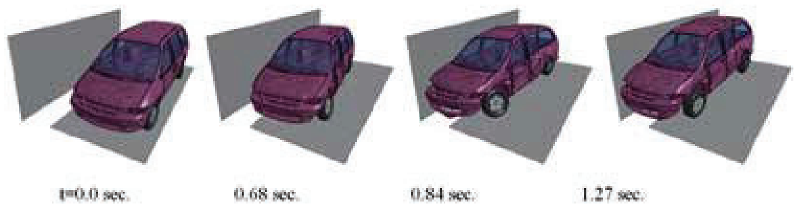

Fig.4 - Motion of the vehicle caused by the pressure of the tsunami

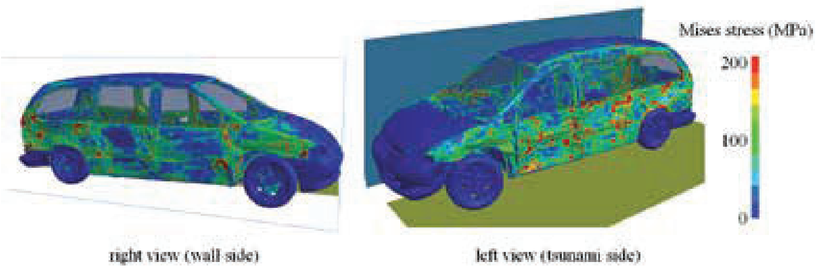

Fig.5 - Deformation and Mises stress distribution of the vehicle at 1.0 second

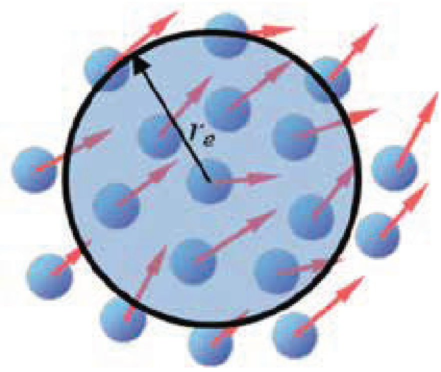

Fig.6 - MPS kernel function

of the simulation. The vehicle is modeled as a rigid body using the STL format geometry. The vehicle is constructed using rigid body particle cluster generated in the given STL geometry. The vehicle is washed away and impacts with a rigid wall.

(2) Pressure history on the surface of the vehicle is obtained from the first stage of the simulation. Pressure is calculated on each rigid particle and it is mapped on the STL vertexes.

(3) Pressure at the particles on the surface of the vehicle is converted to the pressure history load data acting on each finite element. During this data conversion process, we search for the particle closest to a shell element.

(4) Execute crash simulation of the vehicle against the rigid wall in the second phase of the simulation. The vehicle is pushed towards the rigid wall by the pressure load and causes damage.

The flow of the tsunami and the behavior of the vehicle are obtained in the first stage as shown in Fig.2. The vehicle is placed at the position of 1,000 mm from a rigid wall at the beginning of the simulation. Water entries the model from the inflow with a velocity of 4,000 mm/s. The vehicle is washed away and crashes against the wall.

The event interval was 1.35 seconds. With this simulation, we could obtain the pressure history acting on the surface of the vehicle. The pressure was calculated on each particle during the simulation and then it was mapped on the STL vertexes by post processing. After the tsunami simulation, the pressure history was converted into pressure load for the LS-DYNA crash simulation. Figure 3 shows the mapping process of the pressure distribution through particles to finite elements. In the second phase, a transient analysis of the vehicle model using LS-DYNA was executed and deformation and stress distribution was obtained through the simulation. The vehicle motion caused by the tsunami is shown in Fig.4. As the illustration details, the vehicle is pushed towards the wall, hit against the wall and lifted up by the pressure of the tsunami. As a result, large deformation occurs on the vehicle body. Figure 5 shows the deformed geometry and von Mises stress distribution of the vehicle. Large deformation can be seen not only on the right hand side where the vehicle contacts with the rigid wall, but also on the left hand side.

Algorithm of MPS method

The governing equations for incompressible flow are the continuity condition Eq.1 and the Navier-Stokes equations Eq.2,

$$\frac{D\rho}{Dt} = 0 \qquad (1)$$

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2 \boldsymbol{u} + \boldsymbol{g} \qquad (2)$$

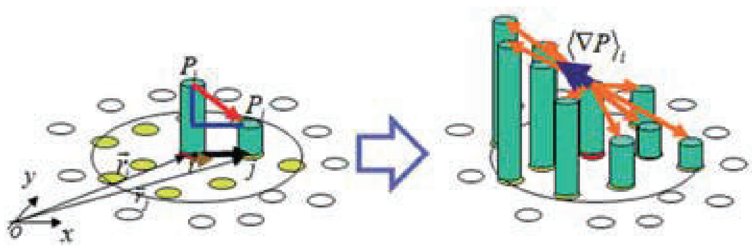

Fig.7 - Particle approximation of gradient

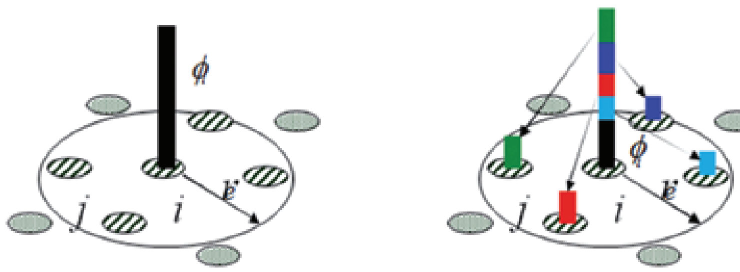

Fig.8 - Particle approximation of Laplacian

where, ρ; density, $\boldsymbol{u}$; velocity, $\boldsymbol{P}$; pressure, $\boldsymbol{v}$; diffusion coefficient, and $\boldsymbol{g}$; gravity. MPS defines the kernel function of the form as,

$$w(r) = \begin{cases} \frac{r_e}{r} - 1 & (r < r_e) \\ 0 & (r \geq r_e) \end{cases} \quad (3)$$

A particle interacts only with surrounding particles within the radius $\boldsymbol{r_e}$. Particle number density is defined using the kernel function as follows:

$$n_i = \sum_{j \neq i} w\left(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|\right) \quad (4)$$

Particle number density is proportional to the fluid density and it should be constant during the computation for incompressible flow. So the coordinates and velocity of the particles are compensated to maintain the particle number density to be constant during each time step. Discretizations of spatial differentials acting on arbitrary scalar ϕ at particle $\boldsymbol{i}$ are defined as the particle interaction approximation model, and can be detailed as follows:

<gradient model>

$$\langle \nabla \phi \rangle_i = \frac{d}{n_0} \sum_{j \neq i} \frac{\phi_j - \phi_i}{\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|} \frac{\left(\boldsymbol{r}_j - \boldsymbol{r}_i\right)}{\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|} w\left(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|\right) \quad (5)$$

<Laplacian model>

$$\langle \nabla^2 \phi \rangle_i = \frac{2d}{\lambda n_0} \sum_{j \neq i} \left(\phi_j - \phi_i\right) w\left(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|\right) \quad (6)$$

where, $\boldsymbol{d}$; spatial dimension (2 or 3), $\boldsymbol{n_0}$; initial particle number density, and λ; correction coefficient. The governing equation Eq.2 is discretized using Eq,5 and 6 and solved under the continuity condition Eq.1 with a semi-implicit algorithm similar to the conventional Simplified MAC method.

Conclusions

An efficient one-way fluid structure coupling technique using Particleworks and LS-DYNA was presented. Because MPS in Particleworks can be applied for incompressible fluid dynamics, this simple procedure can be used widely for product design, development and manufacturing in various industries. The numerical procedure of the particle method MPS was also introduced briefly.

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A memory to Ted Belytschko

Ted Belytschko, Walter P. Murphy Professor and McCormick Distinguished Professor of Computational Mechanics at Northwestern University (Evanston, IL, USA), passed away on September 15, 2014 at the age of 71. His innovative contributions revolutioned the solution of several problems in computational solid mechanics. He developed explicit finite element methods that are widely used in fast dynamics problems like crashworthiness analysis, meshfree methods, multiscale techniques and, recently, the extended finite element method, aimed at dealing with arbitrary singularities and discontinuities independently of the mesh layout. The interest of his scientific production for the community is evidenced by the authorship of more than 500 papers receiving over 33000 citations, with the most cited work having nearly 3000 citations.

Among his many distinguished honors and awards, Belytschko received ASCE's Walter Huber Research Prize in 1977, the Theodore von Karman Medal in 1999, the John von Neumann Medal from the U.S. Association for Computational Mechanics in 2001, the Timoshenko Medal from the American Society of Mechanical Engineers in 2001, the Gauss-Newton Medal from the International Association for Computational Mechanics in 2002 and the William Prager Medal from the Society of Engineering Science in 2011. He was also Editor-in-chief of the International Journal for Numerical Methods in Engineering.

If his scientific excellence is recognized worldwide, it is worth mentioning that he was also a unique teacher and mentor. Many people had the honor of working with him, and I can personally remember the crystalline classes to his students, his daily visits to each of his many Ph.D. and Post-Ph.D. students and the human and scientific respect and consideration he was giving to them. Living in his research group was being part of an amazing flux of ideas and new hints that were transforming the way of looking at the problems in every single day. I can clearly remember the many afternoons spent in discussions and the way he was introducing his new thoughts. He was never overhanging the person in front of him. On the contrary, discussing the different aspects of the problem, an idea was progressively coming out, so that one could not say if the idea was in his mind or was born in the person in front of him. So, remembering his bright smile I feel that I can say, in the name of the many people privileged by having worked with him, thank you, Professor Belytschko, for all you taught us.

Giulio Ventura - Politecnico di Torino