

A Hybrid Finite Element and Mesh-Free Particle Method for Disaster-Resilient Design of Structures

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Abstract The MPS-FE method, which is a hybrid method for Fluid-Structure Interaction (FSI) problems adopting the Finite Element method (FEM) for structure computation and Moving Particle Semi-implicit/Simulation (MPS) methods for free surface flow computation, was developed to utilize it in disaster-resilient design of important facilities and structures. In general free-surface flow simulation using the MPS method, wall boundaries are represented as fixed particles (wall particles) set as uniform grids, so the interface of fluid computation does not correspond to the interface structure computation in the conventional MPS-FE method. In this study, we develop an accurate and robust polygon wall boundary model, named Explicitly Represented Polygon (ERP) wall boundary model, in which the wall boundaries in the MPS method can be represented as planes that have same geometries as finite element surfaces.

Keywords Fluid-structure interaction · Finite element method · Moving particle Semi-implicit/simulation method · Mesh-free particle method · MPS-FE method

1 Introduction

Large-scale facilities such as petrochemical and nuclear power plants, and tsunami evacuation facilities built along coastal regions are vulnerable to water-related disasters. The resulting damage to equipment and instruments has the potential to cause catastrophic harm to people and local society. However, it is economically difficult to completely prevent the effects of disasters of extreme severity. We need quantitative measures to minimize the damages and loss. Detailed numerical computations treating the disasters and damages as Fluid-Structure Interaction (FSI) problems involving free surface flow give us a measure for disaster-resilient design of important structures.

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We have developed a hybrid method for FSI problem with free surface, named the MPS-FE method [1, 2]. This method adopts the Moving Particle Semi-implicit/Simulation (MPS) [3] method, a mesh-free particle method, for free surface flow computation because of its robustness in long-term analyses with moving boundaries, and Finite Element Method (FEM) for structure computation because of its high accuracy and reliability. The method combines the advantages of both methods and achieves efficiency and robustness. These two methods are coupled with a partitioned coupling approach, i.e. the conventional serial staggered (CSS) scheme [4], which can set different time step sizes for the fluid and structure computations.

The conventional MPS-FE method [1], in which MPS wall boundary particles and finite elements are overlapped in order to exchange information on fluid-structure interfaces, has difficulty in dealing with complex shaped fluid-structure interfaces, because the wall particles have to be set in an orthogonal and uniform grid manner. In addition, forces on fluid-structure interfaces are not balanced when the pressure on the walls is calculated in the conventional MPS-FE method. As the next step, we adopted existing polygon wall boundary models [5, 6], which can treat a wall boundary as an arbitrary plane, and improved the MPS-FE methods so that the fluid and structure interfaces are consistent. However, the existing polygon wall boundary models cannot satisfy the pressure Neumann or the slip/no-slip boundary conditions, so these cause instability near the boundaries and deteriorate the accuracy.

In this study, we developed a new polygon wall boundary model for fully explicit algorithms (Explicit-MPS [7]: E-MPS), called the Explicitly Represented Polygon (ERP) wall boundary model [8] to compose more accurate MPS-FE method. The ERP model is formulated such that it satisfies the pressure Neumann boundary condition and the slip/no-slip boundary condition, without requiring the generation of virtual particles or treating angled edges as exceptional cases. Moreover, the ERP model eliminates the problem of force imbalance on the boundaries, which occurs in conventional models.

2 ERP Wall Boundary Model for Explicit-MPS Method

Regarding the wall boundary treatments, research has made greater progress for the SPH method [9], which is one of mesh-free particle methods. The repulsive-force model [10] has been developed in order to avoid penetration of fluid particles across wall boundaries. Although this model is relatively easy to implement, it causes the instability of fluid particles near wall boundaries because the boundary conditions are not satisfied. On the other hand, the ghost (mirror) particle approach [11] is widely used to satisfy the boundary conditions on walls. In this approach, virtual particle is generated at reflectional position across the wall of each fluid particle. These mirror particles are given pressure and velocity values so that the pressure Neumann boundary condition and slip/no-slip condition are satisfied. However, this

approach has several problems, including a high computational cost caused by the need to generate virtual particles, and leakage of particles at the angled edges of surfaces.

Regarding polygon wall boundary models in the MPS method, Harada et al. [5] derived the force exerted on a fluid particle from a wall from impulse-momentum relationship at the particles near the wall. This force modeling can be classified as repulsive-force model, so Harada's model has the same problem of the instability and strange behavior of fluid particles near the wall. Yamada et al. [6] focused on the E-MPS method and they proposed another formulation. Although this is a natural expansion of the MPS differential operator models, the model causes excessive pressure oscillations.

The ERP model is based on the mirror particle approach and can satisfy the boundary conditions on walls without virtual particles, and it is versatile enough to treat arbitrarily shaped boundaries and arbitrary movements. The ERP model adds a repulsive force adaptively only when the boundary conditions are not satisfied near the angled edges. The ERP model has the following characteristics:

- Wall boundaries are represented explicitly.
- Generation of virtual particles and the need to make special adaptations for angled edges are not required.
- The pressure Neumann boundary condition and the slip/no-slip condition on the walls are satisfied.

3 Verification of the ERP Model

To verify the accuracy of the ERP model applied to the E-MPS method quantitatively, we analyzed a hydrostatic pressure problem in a rectangular vessel. The numerical results were compared with the theoretical solution

$$p = \rho |g| h$$

where ρ is the fluid density, g is the gravitational acceleration vector, and h is the depth of the static water surface. The initial configuration, in which the depth of the rectangular vessel is 0.1 m and the width is 0.04 m, is illustrated in Fig. 1. In the E-MPS computation, weak compressibility causes vertical vibrations of the fluid surface. To reach the static state as quickly as possible, we chose a relatively high value for the kinematic viscosity. The conditions used in the analysis are listed in Table 1, in which l^0 is the initial particle spacing.

Figure 3 shows the pressures of fluid particles computed by (a) the ERP model, (b) the ERP model using only the repulsive force, (c) Harada's model, and (d) Yamada's model. These are the results at the 200,000th step, at which the pressure field can be regarded to be in a steady state. In Fig. 2, snapshots obtained

Fig. 1 Hydrostatic pressure: initial configuration

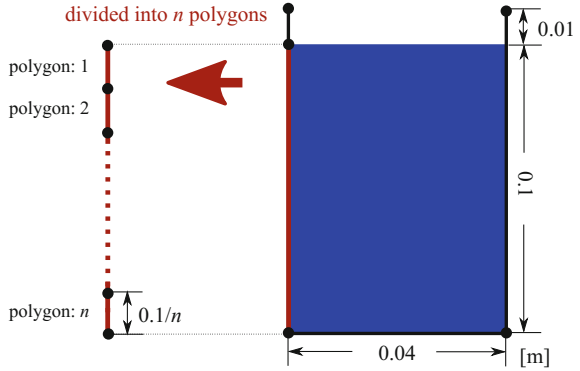
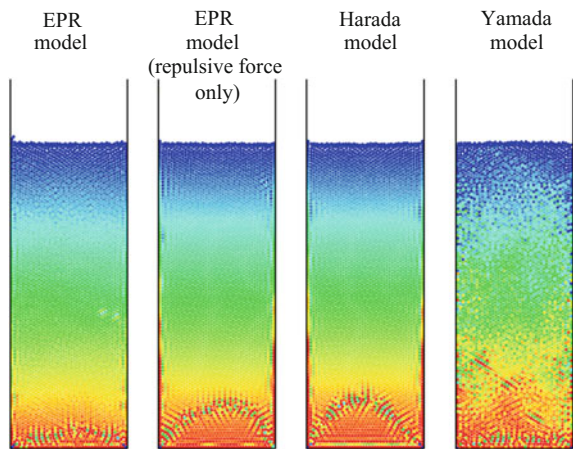


Table 1 Hydrostatic pressure: analysis conditions

Time step width	5.0×10^{-5} (s)
Number of particles	4000
Particle spacing	1.0×10^{-3} (m)
Effective radius	$2.9l^0$ (m)
Fluid density	1.0×10^3 (kg/m ³)
Kinetic viscosity	1.0×10^{-4} (m ² /s)
Gravitational acceleration	9.8 (m ² /s)
Sound speed coefficient	9.44 (m/s)
Repulsive coefficient	1.0×10^7 (N/m ³)

Fig. 2 Hydrostatic pressure: visualization of results



by each models at the 200,000th step are shown; the pressure on the fluid particles is indicated by color (unit [N/m²], min: 0, max: 1,000).

As indicated in Fig. 3b, c, the results from using only the repulsive force show the same tendency as those from Harada’s pressure gradient model, which is one of

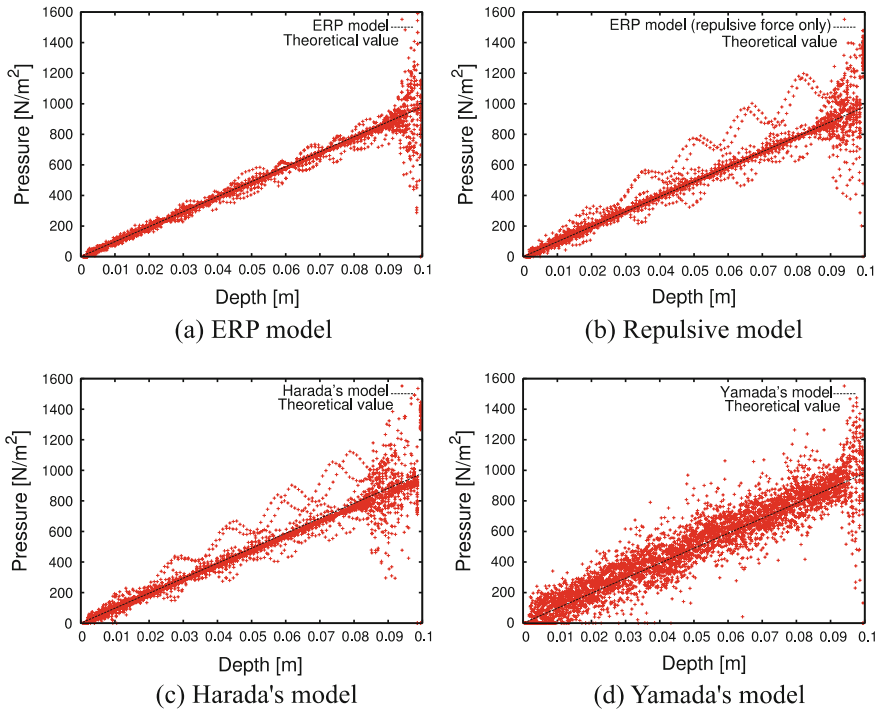


Fig. 3 Hydrostatic pressure: pressure on particles

the repulsive force models as we mentioned. Both of the results exhibit two strange lines that indicate pressures that are higher than the theoretical values. These results indicate that the pressures on the particles in contact with polygons have not been evaluated correctly, as shown in Fig. 2. Therefore, the model using only the repulsive force encounters the same problems as are found with Harada’s model. On the other hand, Fig. 3d shows that Yamada’s pressure gradient model results in a disturbed pressure field that has a wide dispersion compared to those of the other methods.

Unlike the existing polygon wall boundary models, the ERP model does not have the problems that occur with Harada’s and Yamada’s models, and it obtains a better pressure distribution that is in agreement with the theoretical solution. The results of the ERP model are also in better agreement with the theoretical solution. This is because the pressure gradient in the ERP model satisfies the pressure Neumann boundary condition, whereas the pressure gradient obtained using the existing polygon wall boundary models do not satisfy it rigorously. The results of the polygon wall boundary model involving the ERP model, however, have highly dispersed pressures near the bottom of the vessel, because the accuracy deteriorates at the angled edges of polygons. The influence of the edges can be reduced by enhancing the spatial resolution by using smaller particles.

4 Conclusions

In this study, we developed and verified the Explicitly Represented Polygon (ERP) wall boundary model for the E-MPS method. It can deal with arbitrarily shaped boundaries and movements, and it can accurately impose boundary conditions for free-surface flow analysis.

The ERP model is formulated so as to satisfies the pressure Neumann boundary condition and the slip/no-slip boundary condition, without requiring the generation of virtual particles or treating angled edges as exceptional cases.

For verification of the proposed model, we conducted simulations for a hydrostatic pressure problem. The results were compared with the theoretical values and the results of other models. We confirmed that the boundary conditions of the ERP method were appropriately modeled, and the E-MPS method with the ERP model can achieve adequate accuracy.

Now, we have been developing a more accurate and robust MPS-FE method applying the ERP model, and a large-scale parallel MPS-FE analysis system using the large-scale parallel code for the E-MPS method (HDDM_EMPS [12, 13]) and FEM (ADVENTURE_Solid [14, 15]). This system makes it possible to conduct robust simulations of three-dimensional fluid-structure interaction. An example is shown in Fig. 4, which is a three-dimensional simulation of dam break and an elastic column with constraints on the bottom surface.

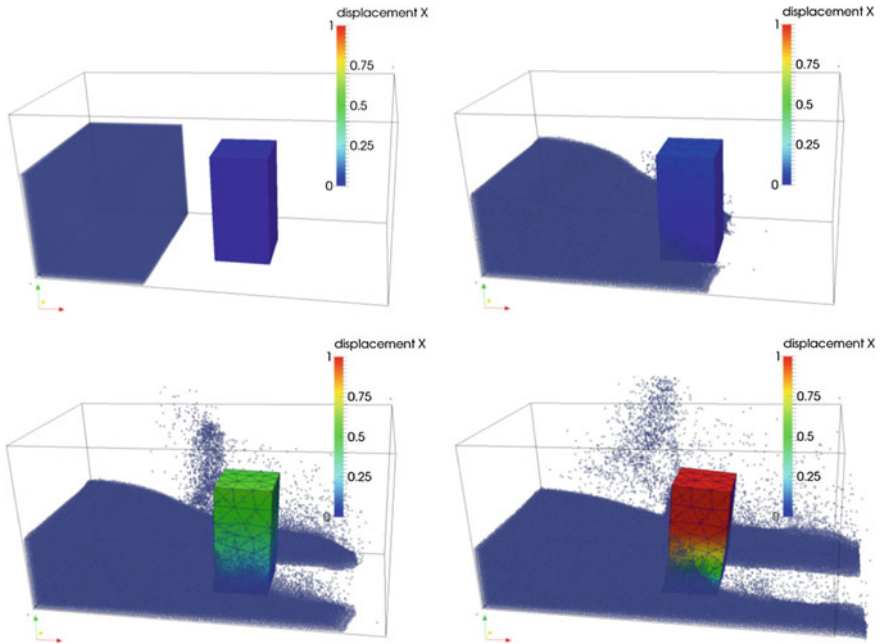


Fig. 4 Example of three-dimensional FSI simulation using the MPS-FE method

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