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Numerical study of MPS method with large eddy simulation for fluid solid coupling problem

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Abstract. The Moving-Particle Semi-implicit method (MPS) is a kind of meshless Lagrangian calculation method. This method uses particles instead of mesh. In the pretreatment it works simply and conveniently and has high computational efficiency. In practical engineering, many of fluid problems are turbulent flows. Large eddy simulation is a major means of studying turbulence. Fluid-structure coupling is an independent branch of mechanics combined with fluid dynamics and solid mechanics, which is the hot and difficult area of research in many fields at present. In this paper, for the numerical simulation of turbulent flow with interaction of fluid-structure, the modified MPS-LES method is applied in two dimensional dam-break problem. It proves that MPS-LES method can be extended on solving the fluid-solid coupled problem.

1. Introduction

Fluid-structure coupling problem is common in the field of ship engineering and marine technology. In computational structural mechanics, the most widely used numerical discretization method is finite element method. But in computational fluid dynamics, it primarily adopts the finite difference method or finite volume method. Therefore, it not only needs to take both fluid-structure interactions in numerical analysis but also need in the coupling between the methods into account. In the process of fluid-structure coupling analysis, Discontinuous interface between the fluid and solid grid will be produced. In dealing with such time-varying discontinuous interface, the grid method mainly restructures the grid in every calculated step so as to guarantee the consistency of grid lines with the interface after the deformation. The main strategy calculation method based on grid is used that reconstruction in each calculation step in the grid, to ensure that the grid line is still consistent with the deformation of the interface. It will not only face the numerical difficulties, but also decreases accuracy. Sometimes too much mesh deformation will result in distortion and grid computing terminates.

MPS is a new Lagrangian particle method, which was first proposed by Koshizuka, S, Oka, Y.[1] in 1996. Due to a very extensive applications of MPS, after it was proposed[1],[2] , it has been widely used in many research fields. In 1999, Gotoh[3] used the MPS method to simulate wave propagation. In practical engineering problems, a lot of flowing fluid is turbulent flow, and large eddy simulation is a major means of research on turbulence. With respect to the ordinary governing equation, subgrid Reynolds stress terms are added in Large eddy simulation (LES), so large eddy simulation method is very suitable for MPS. In 2001 Gotoh[4], for the first time, applied large-eddy turbulence model to MPS method. In 2001, Chikazawa[5] adopted MPS method in the fluid-structure interaction, and It is the first time that this method is applied in computational structural mechanics. In 2008 Pan Xu Jie [6][7][8][9] has been carried out research on the main problems existing in MPS method. He developed a new technique of free surface recognition. In 2013 based on MPS-LES method ,Yu Qian[10] simulated the impact of a wedge into the water problem. In the ocean wave environment, fluid-structure coupling numerical simulation has great significance on the interaction between ocean wave and marine construction. During the early development of the MPS method, many studies have mainly focused on the simulation of fluid. But research on fluid-structure coupling problems are very rare. This paper has initiatively applied MPS method with Large Eddy Simulation into the elastic fluid-structure coupling calculation. The compared and analyzed simulation results show that MPS-LES method can be well applied in the solution of fluid-structure coupling problem.

2. MPS method

Adopted to deal with the fluid-structure coupling problem, First, ignore the properties of the solid particles, they're treated as fluid particles, the MPS method can also be adopted for all particles. When using large eddy simulation method to simulate the turbulent flow, the fluid control equation with equation should be added sub-grid Reynolds stressing force item. The calculation method for fluid is the same as our published paper, detail see Ref[9]. The speed and position of solid particles is modified in accordance with elastomer control equation.
The control equations of elastomer is as follows:

$$\rho\frac{Dv_\alpha}{Dt} = -\frac{\partial p}{\partial x_\alpha} + \frac{\partial \sigma_{\alpha\beta}}{\partial x_\beta} \tag{1}$$

where ρ is the material density, p is an isotropic pressure which is got in particle location , $\sigma^{\alpha\beta}$ is unisotropic components of stress tensor .

$$\sigma_{ij} = 2\mu\varepsilon_{ij}^n = \frac{2\mu(u_{ij}\cdot r_{ij})r_{ij}}{\left|r_{ij}^0\right|\left|r_{ij}\right|^2} \tag{2}$$

$$\tau_{ij} = 2\mu\varepsilon_{ij}^s = 2\mu\frac{u_{ij}}{\left|r_{ij}^0\right|} - \sigma_{ij} \tag{3}$$

$$p = -\lambda(\varepsilon_{rr})_i = -\lambda\frac{d}{n^0}\sum_{j\neq i}\frac{u_{ij}\cdot r_{ij}}{\left|r_{ij}^0\right|\left|r_{ij}\right|}w(\left|r_{ij}^0\right|) \tag{4}$$

σ_{ij} and τ_{ij} are the Normal stress and shear stress to the particle i and j , and u_{ij} is the variation of the relative position between the particles, r_{ij} is the relative position between particle i and j , d is the number of space dimension.
The acceleration produced by the force between particles is:

$$\left[\frac{\partial v_i}{\partial t}\right]_n = \frac{2d}{\rho_i n^0}\sum_{j\neq i}\frac{\sigma_{ij}}{\left|r_{ij}^0\right|}w\left(\left|r_{ij}^0\right|\right) \tag{5}$$

$$\left[\frac{\partial v_i}{\partial t}\right]_s = \frac{2d}{\rho_i n^0}\sum_{j\neq i}\frac{\tau_{ij}}{\left|r_{ij}^0\right|}w\left(\left|r_{ij}^0\right|\right) \tag{6}$$

$$\left[\frac{\partial v_i}{\partial t}\right]_p = -\frac{d}{\rho_i n^0}\sum_{j\neq i}\frac{(p_i + p_j)r_{ij}}{\left|r_{ij}^0\right|\left|r_{ij}\right|}w\left(\left|r_{ij}^0\right|\right) \tag{7}$$

$\left[\frac{\partial v_i}{\partial t}\right]_s$ is the shear acceleration , $\left[\frac{\partial v_i}{\partial t}\right]_n$ is normal acceleration, $\left[\frac{\partial v_i}{\partial t}\right]_p$ is the acceleration produced by the pressure.

Updating the particles' rotation angle speed, rotation angle, speed, and coordinate position, could be described as follows:

$$v_i^{n+1} = v_i^n + \Delta t\left[\frac{\partial v_i}{\partial t}\right]^n \tag{8}$$

$$r_i^{n+1} = r_i^n + \Delta t v_i^{n+1} \tag{9}$$

3. Results of numerical simulation

Dam-break model is shown below, the initial water column length and width were 0.292m, 0.146m, height of 0.08m, width of 0.012m, flat located at x = 0.292m. Set flat elastic modulus of 1.0*pa, Poisson's ratio of 0.0, a density of 2.5 times than that of water. Take the dame break model to particle model .The results shown in figure 1, the particle spacing $l_0 = 0.0025m$, $r_e = 2.1l_0$, time step takes 0.0001s. In this simulation, three models have been selected, they're ideal fluid, the viscous laminar flow and LES(large eddy simulation) based on Smagorinsky eddy viscous model respectively.

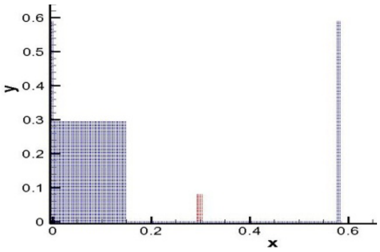


Figure 1.System of dam break example with elastic structure

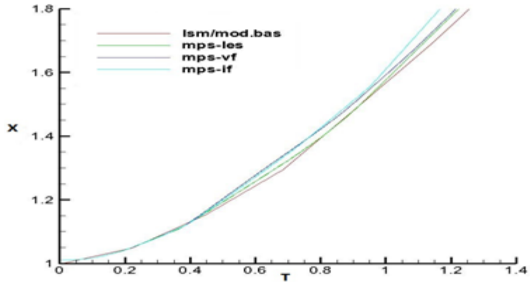
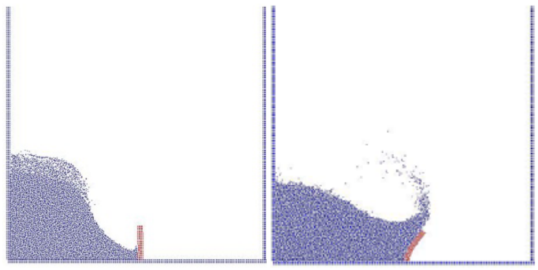


Figure 2. Leading edges of the water column collapse

See figure 2 , no matter what the conditions is selected in simulation, the water column quickly collapsed under the force of gravity, but in different simulated conditions, we can see a slight difference in the speed of the collapse, in which the ideal fluid was first to reach flat position. Because the ideal fluid does not consider any sticky, it collapse faster. The large eddy simulation in addition to viscosity, takes eddy viscosity into account, which is the largest internal energy consumption, so it arrives at the flat position latest. Time and distance in the figure is non-dimensional (X=x/l,T=t(2g/l)1/2).The results are in agreement with reference [11](shown as ism/mod.bas in fig.2)
Large Eddy Simulation of dam-break fluid-structure coupling calculation results are shown in figure 3, it can be seen from the figure that when applied on coupled fluid-structure calculations, The improved MPS method based on large eddy simulation can accurately simulate the large deformation of fluid free surface accompanied with the breaking and splashing, and elastic deformation of elastic plate under the impact of fluid.



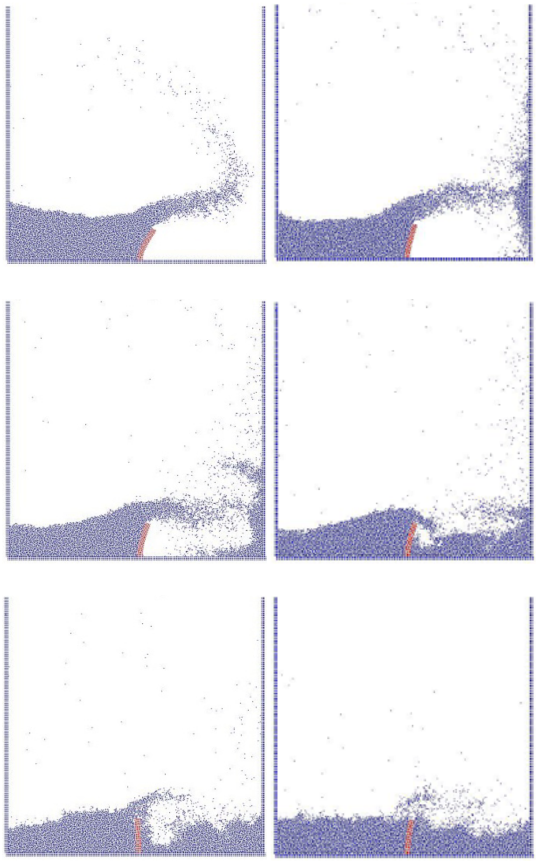


Figure 3. Interaction between dam-break impact elastic plate.

Under the impact of fluid the plate at the top will produce deformation, and figure 4 shows the variation of flat plate at the top displacement with time. The top of flat deform by the impact of water compared with other numerical results [12] and is illustrated in figure 4. Under the impact load of flow, the displacement and direction of the top of the plate vary with the time, reciprocating oscillating movement occurs at the top of flat plate.

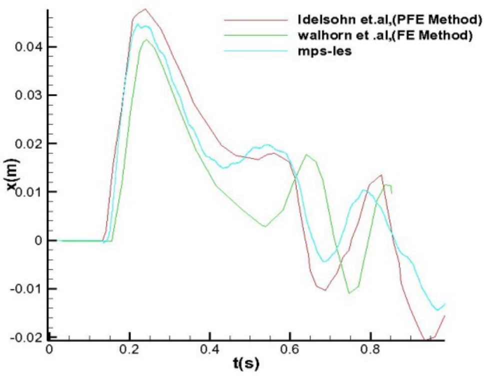


Figure 4. History of the displacement

4. Conclusion

In this paper, the fluid-structure interaction of dam-break model is simulated by large eddy simulation moving particle semi-implicit method, in which the calculation of attacking pressure were improved and oscillation were reduced. And the position of head of the fluid, and the elastic deformation and displacement of the plate were analyzed. The MPS method based on large eddy simulation is applied on the dam-break fluid-solid coupling calculation, accurately simulates large deformation of the fluid free surface even with the breaking and splashing situation, and the deformation of elastic plate under the impact of the fluid. It confirmed that the moving particle semi-implicit method combined with large-eddy simulation applying to fluid-structure interaction problems is reasonable and correct.

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