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Smoothed particle hydrodynamics and its applications in fluid-structure interactions[*]

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Abstract: In ocean engineering, the applications are usually related to a free surface which brings so many interesting physical phenomena (e.g. water waves, impacts, splashing jets, etc.). To model these complex free surface flows is a tough and challenging task for most computational fluid dynamics (CFD) solvers which work in the Eulerian framework. As a Lagrangian and meshless method, smoothed particle hydrodynamics (SPH) offers a convenient tracking for different complex boundaries and a straightforward satisfaction for different boundary conditions. Therefore SPH is robust in modeling complex hydrodynamic problems characterized by free surface boundaries, multiphase interfaces or material discontinuities. Along with the rapid development of the SPH theory, related numerical techniques and high-performance computing technologies, SPH has not only attracted much attention in the academic community, but also gradually gained wide applications in industrial circles. This paper is dedicated to a review of the recent developments of SPH method and its typical applications in fluid-structure interactions in ocean engineering. Different numerical techniques for improving numerical accuracy, satisfying different boundary conditions, improving computational efficiency, suppressing pressure fluctuations and preventing the tensile instability, etc., are introduced. In the numerical results, various typical fluid-structure interaction problems or multiphase problems in ocean engineering are described, modeled and validated. The prospective developments of SPH in ocean engineering are also discussed.

Key words: Smoothed particle hydrodynamics, ocean engineering, fluid-structure interaction, bubble dynamics, underwater explosion, hydrodynamics

Introduction

Smoothed particle hydrodynamics (SPH) method and its related variants have been developing as a new generation of computational fluid mechanics (CFD) solvers for complex hydrodynamic problems for decades[1-9] and have been widely applied in a wide range of engineering problems[10-17]. The present work is devoted to a review of the recent developments and achievements of SPH methodology and an introduction to its typical applications in fluid-structure interactions in ocean engineering.

The distinctive features of the problems in ocean engineering are mostly linked to the existence of a free fluid surface (when the air phase is neglected) and moving or deforming wall boundaries. To deal with these kinds of problems, different numerical solvers based on Eulerian, Lagrangian or Arbitrary Lagrangian Eulerian (ALE) formulations are developed[18-21]. These numerical solvers are mesh-based or meshless. The Eulerian mesh-based methods may demand complex algorithms and huge computational costs in the tracking of the free surface, especially in simulations with drastic free surface splashing jets. While in the Lagrangian mesh-based solvers, the fluid surface and boundary are explicitly tracked. However, the problems of the Lagrangian mesh distortion and re-mesh in some violent fluid-structure interaction problems may become cumbersome. By contrast with the mesh-based

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methods, in Lagrangian meshless methods, e.g. SPH[22] or Moving Particle Semi-implicit method (MPS)[23], inherently the complex algorithm of the free surface tracking and the mesh distortion are avoided. The Lagrangian motions of the material particles also supply a convenient way for the analysis of the flow features in a Lagrangian way, which is another merit compared to the Eulerian methods[24,25]. As SPH is a distinct representative of Lagrangian meshless methods and it has been widely applied in the field of hydrodynamics recently. Moreover, it has been proven in Souto-Iglesias et al.[26,27] and Shao and Gotho[28] that SPH and MPS are closely related, or in other words, equivalent, hereinafter our review and discussion are mainly based on SPH and its applications in fluid-structure interaction problems in ocean engineering.

In the present review, the problems solved by SPH are classified into two categories namely hydrodynamic problems (e.g. water-body interactions, water impacts, water entries and exits, flow past bodies, etc.) and explosion problems (e.g. underwater explosions, contact explosions, etc.). The two categories of problems have obviously different features. For the former, the conservation of mass, momentum and energy of the numerical solver is crucial for maintaining the numerical accuracy and stability in a long-term simulation, while for the latter, the fluid should be considered as compressible and a large transient and violent deformation of the structure (fluid boundary) are usually involved.

For long-term hydrodynamic problems, expensive computational costs are usually encountered. To obtain a fast and efficient simulation, on the one hand the adoption of advanced computing platforms can be crucial, recently different high performance computing techniques, e.g. OpenMP[13,29], MPI[30,31], CUDA[32-34], OpenCL[11] are introduced and applied in the framework of SPH method to accelerate the computing. On the other hand, different algorithms are also proposed to reduce the amount of computation by SPH itself. In the weakly-compressible SPH (WCSPH) method, e.g. the well-known δ- SPH scheme, a fourth-order Runge-Kutta time-integration is adopted, which allows for a relatively large CFL coefficient for the time step[35-37]. While in the Incompressible SPH (ISPH) method[38-41], the time-step is not restricted by the stability reason but by the accuracy reason[42,43]. The time step of ISPH can be 5 times larger than WCSPH, however in each time step, the ISPH requires a more expensive computational cost due to the tracking of the free surface particles[44] and the solving of the Poisson equation[45]. Finally, after a compromise between the stability and accuracy, an equivalent efficiency can be achieved between WCSPH and ISPH[43]. Another cause that restricts the efficiency of SPH is the request for a uniform particle distribution to satisfy the conditions in the particle approximation, see the theoretical analysis in Liu and Liu[46]. As has been recently explored in Antuono et al.[47], only when the particle distribution is in a sufficiently low disorder, a convergence rate between 1 and 2 can be obtained. This characteristic means that in SPH the multi-resolution for the particle scale cannot be as straightforward as the adaptive mesh-refinement widely used in the mesh-based CFD solvers[48]. However, recently different numerical techniques are developed to address the adaptive particle refinement (APR)[49-51], in which not only the total computational cost is reduced but also the local accuracy is drastically improved. The achievements of APR in SPH make the large scale simulation, which is quite common in ocean engineering applications, become possible.

The explosion problem is another important branch in the fluid-structure interaction problems in ocean engineering, e.g. the high-velocity impact[52], underwater explosion[53-56], contact explosion[16], etc. In the simulation of these problems SPH can be more reliable than other mesh-based solvers[46,56,57]. A proper equation of state is important for these problems since the fluid phases are usually regarded as compressible. Besides, SPH approximation formulations of high accuracy is also crucial since a large deformation of the material is usually involved, such as the fluid surface splashing, fragmentations, moving discontinuities, large inhomogeneity and structure fractures. In these circumstances, perhaps the particles distributions are quite disordered or the kernel functions near the boundary can be truncated. Therefore, recently SPH equations of high accuracy[58-61] are developed to resolve these problems.

To model the structure responses in fluid-structure interactions, different methods have been developed. The first way is to adopt an SPH-FEM coupling[52,53,62-65]. The second way is to employ another particle based method namely shell SPH to model the structure[66,67]. The third way is to adopt an elastic SPH model to model the response of an elastic structure. Recently, this technique has been widely adopted in the sloshing or dam breaking problems considering an elastic baffle[68,69]. Finally, it is worth mentioning in Yang et al.[70-72], a coupling method of SPH and element bending group (EBG) is developed for modeling the interaction between viscous flows and flexible structures with free or fixed ends.

The consideration of the air phase above the fluid surface is also highlighted in the present work. Indeed, in most of the numerical simulations for free surface flows, the air effect is not considered since it is difficult to treat and also brings more expensive computational cost. Recently, in Marrone et al.[73], it is pointed out that energy evolutions can be similar when inclu-