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An accurate and efficient SPH modeling of the water entry of circular cylinders

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ABSTRACT

The present work is dedicated to the enhancement and application of the recently developed δ^{+}-SPH scheme for two and three dimensional water entry problems. The cylinder surface presents a circular shape and therefore the position where the flow separation happens is tightly related to the implementation of the boundary condition. A special treatment for the particle shifting between fluid and solid wall is highlighted. Adaptive particle refinement (APR) is applied in this work to reduce the computational cost. It is found that, APR and the δ^{+}-SPH scheme benefit to each other. That is to say the former reduces the computing cost of the latter while in return the latter solves the problem of particle disorder of the inactive particles of the former. Thanks to the combination of APR and δ^{+}-SPH especially in three dimensional (3D) cases, the overall computational cost is significantly reduced while sufficiently fine particle resolution can be obtained in the flow region characterized by large pressure gradient close to the structure surface. The fairly good agreements between the SPH results and the experimental data prove the present SPH model to be a reliable tool in accurately solving the fluid–structure interacting problems in ocean engineering.

1. Introduction

The water entry is a classic problem which is tightly related to many applications in naval architecture and ocean engineering, e.g. the ship hull slamming, the wave impact on offshore structures, the launch of underwater vehicles, the ditching of aircrafts, etc. (see, e.g. [58,59,52,33]). The reason researchers pay so much attention to this problem is mainly because of the development of high pressures during the impact with the free surface which can threat the structure integrity. Another reason is related to the prediction of the body trajectory. Indeed, during the water entry process, the predesigned trajectory may be significantly altered by the complex hydrodynamic forces acting on the body.

Experimental tests [58,59], analytical models [22] and numerical methods [52] are the three main means for studying this problem. Experimental tests always give the most reliable results which have been largely used in the validation of mathematical or numerical models and, also, in practical applications. However, expensive costs and long operating durations are the two main obstacles which fostered research on alternative methods. Several analytical models have been developed but they are still limited to simplified problems in ideal conditions. Due to the limitations of the first two strategies, recently there are more and more computational fluid dynamics (CFD) solvers developed to simulate the water entry process. CFD methods can avoid the scale effect in experiments and, in principle, are able to consider more complex scenarios than analytical methods. Zhu et al. [63], Nguyen et al. [41] and Iranmanesh and Passandideh-Fard [18] modeled different water entry/exit problems using Eulerian mesh-based solvers for modeling of the fluid region. In these solutions, when the free surface deformations are important, the free surface sharpness can be over diffused. On this aspect Lagrangian mesh-free models can provide a valuable contribution.

Smoothed particle hydrodynamics (SPH) method is a representative mesh-free CFD method which has been widely used for solving fluid–structure interaction (FSI) problems, see, e.g. [62,45,36,17,61,37,44]. In this context, an early study of wedge water entries was carried out by Oger et al. [42] using a weakly compressible SPH (WCSPH) method. Skillen et al. [48] studied the water entry of a cylinder and a wedge in two dimensions using an incompressible SPH (ISPH) method. Lind et al. [26] used the same incompressible liquid model combined with a compressible model

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for the air for studying wave slam problems. Khayyer and Gotoh [19] proposed a compressible-incompressible particle method for problems of impacts of rigid plates on water surface. Most of the studies of water entries in the previous literature are limited to two dimensional (2D) cases and the body motions are mostly in one degree of freedom. Three dimensional (3D) studies are still rare due to the challenging problems related to the treatment of 3D boundaries and large computational costs. Recently, Marrone et al. [33] conducted 3D SPH simulations of water entries of complex bodies using a large number of particles, highlighting the importance of choosing a correct sound speed in the prediction of the peak pressure in the initial stage of the impact. The time durations of the water entry process in that work are, however, relatively short.

In order to obtain accurate solutions, sufficiently fine particle resolutions have to be arranged in flow regions characterized by large velocity/pressure gradients. In the load assessment in water impact problems, a fine particle resolution close to the structure surface contributes to an accurate evaluation of the pressure peak of the impact load. However, this requires expensive computational costs. In addition to that, the water entry of rigid bodies usually occurs in a free field, that means the fluid domain should be large enough and this also involves large particle numbers, unless an adaptive particle refinement (APR) is implemented.

In Vacondio et al. [57], a dynamic particle coalescing and splitting was firstly implemented to model variable resolution in SPH and the particle shifting technique (PST) was also shown to perform well in multi-resolution problems. Later, the same scheme was extended to three dimensional problems [55,56]. However, the APR technique implemented in the present work is an overlapping particle technique which was first proposed by Barcarolo et al. [4] and has been recently improved by Chiron et al. [7].

The PST plays an important role in regularizing the particle distribution in the flow region with large velocity/pressure gradients which typically occur in the viscous boundary layer or in the impact region. PST was first proposed in [40] in the framework of finite volume particle method (FVPM) and then extended to the ISPH method in [60]. Through a modification of the shifting law at the free surface, PST can be also applied to free surface flows in the ISPH (see, e.g. [27]) or moving particle semi-implicit (MPS) method [20]. In the latter, Khayyer et al. [20] proposed a more accurate modification for the particle shifting on the free surface. PST was firstly combined with WCSPH by Shadloo et al. [46] for the modeling of viscous flows past solid bodies. The combination of PST and SPH model with density diffusive term [38] in Vacondio et al. [57] showed good accuracy for viscous flow problems in confined regions. In Sun et al. [51], PST was reformulated based on the formulation of Lind et al. [27] for the weakly compressible framework and then combined with δ-SPH [3,29] and the APR for the modeling of both confined and free-surface flows. The new SPH variant was called δ^+-SPH and it contributes to further improve numerical accuracy, stability and efficiency under which challenging benchmarks can be well solved (see more in [51]). It is also worth noting that the treatments for the particle shifting on the free surface are similar between Khayyer et al. [20] and Sun et al. [51], which means this technique works well for both incompressible and weakly compressible models.

In [51], 2D benchmarks of the flow past immersed bodies are modeled and validated. However, the application of δ^+-SPH scheme to FSI problems with a free surface intersecting the body wall still needs testing. Cylinder water entry is a representative test case where the rigid body with a curved surface gradually pierces the free surface. In this case, the location of the intersection between the free surface and structure boundary changes during the water entry process. Similar circumstances have also been studied in [5]. In that work, the kernel truncation on the free surface has to be mirrored to the ghost particles in order to correctly treat the intersection between the free surface and solid boundary. However, there are still some open questions. For example, it is worth investigating how the pressure interpolation for the ghost particles will affect the numerical solution of this problem. Further, the fluid particle re-positioning by PST may also play an important role in altering the intersection between free surface and the body. In Skillen et al. [48], ISPH combined with the PST was applied to model body-water slamming problems, but the numerical treatment at the intersection between free surface and the body was not presented in details. The latter aspect will be studied specifically in Section 3 of this paper.

Another motivation of the present work is to test the δ^+-SPH scheme in modeling the whole evolution of the rigid body from the initial water entry to the later settlement in a relatively large duration in three dimensions (3D). That means we are interested in global quantities related to the kinematics of the body other than only focusing on the local slamming in a relatively small region and in a short duration, see, e.g. [33]. In the former case, a large fluid domain allowing a large displacement of the body is needed, which implies a more expensive computational cost. Indeed, as a particle method, SPH is suitable for such kind of problems where large displacements of the body and violent deformation of the free surface occur, avoiding the problem related to the mesh-distortion in mesh based methods or the difficulties related to the free-surface tracking/detection in Eulerian solvers (see more discussions in [52]).

Generally in FSI problems, an accurate evaluation of the forces and torques on the body is fundamental in accurately predicting the body trajectory during the water entry. A sufficiently fine particle resolution is therefore needed, which involves very large particle numbers if APR is not adopted, even in 2D simulations (see, e.g. [5]). Further, since Crespo et al. [11], the adoption of GPU (Graphics Processing Unit) has become quite popular to accelerate SPH simulations. Recently in Crespo et al. [10], a GTX Tesla K40 GPU has been adopted to accelerate 3D FSI simulations in the case of uniform particle resolutions. Vacondio et al. [55] combined the techniques of variable particle resolution and GPU together for the modeling of 3D hydrodynamic problems and provided a way to apply SPH into the real engineering practice. However, in the present work, thanks to the reduction of the computational costs by APR, it is shown that accurate and efficient modeling of 3D water entry problems can be also carried out even on a desktop computer (Inter(R) Core(TM) i7-4790 processor, see more details in Sections 4 and 5) in less than 24 h. In the future, following Vacondio et al. [55], the present APR technique will be combined with GPU programming in order to drastically decrease the computational time required.

In the present work, a single-phase SPH model has been adopted and the effect of air entrained in the water entry process has been neglected. The adoption of the single-phase SPH model contributes to the reduced the computational costs and the model complexity. It has been shown in Marrone et al. [32] that the for a dam-breaking problem the energy decay is similar when including or not the presence of air, but this conclusion is not general and applies only to energy dissipation aspects. In fact, as far as the forces on a slamming body are concerned the air can play a critical role as described in, e.g. [26,33].

The present paper is organized as follows. In Section 2 the δ^+-SPH scheme is briefly recalled and enhanced for the modeling of water entry problems. Then, in Section 3 the δ^+-SPH scheme is firstly tested on 2D cylinder water entries and a detailed study of the influence of different numerical techniques is provided. It is found that PST is a key factor for enhancing APR performances (see also [7]). Further, the pressure for the fixed ghost particle (FGP) and the particle shifting on the fluid–body surface are two factors which are shown to affect the flow separation from the rigid body. In Section 3.4 the final 2D simulation is validated against experimental data. In Sections 4 and 5 the 3D problem of the cylinder water entry is studied for several configurations, considering also