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A Cartesian cut cell based two-way strong fluid–solid coupling algorithm for 2D floating bodies

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ABSTRACT

In a recent paper Kelly et al. (2015) [PICIN: A Particle-In-Cell solver for incompressible free surface flows with two-way fluid–solid coupling. SIAM Journal on Scientific Computing 37 (3), B403–24.] detailed the PICIN full particle Particle-In-Cell (PIC) solver for incompressible free-surface flows. The model described in that paper employed a tailored version of the Distributed Lagrange Multiplier (DLM) method for the strong coupling of fluid–solid interaction. In this paper we propose an alternative strong fluid–solid coupling algorithm based on a modification to the cut cell methodology that is informed by the variational approach. The solid velocity flux/integral on the boundary is expressed purely in terms of pressure leading to a revised pressure Poisson equation that is discretised in a finite volume sense. This approach allows the PICIN model to simulate the motion of floating bodies of arbitrary configuration. 2D test cases involving floating bodies with one or more degrees of freedom (DoF) are used to validate the modified PICIN model. The results presented show that the modified PICIN model is able to both efficiently and robustly predict the motions of surface-piercing floating structures under either regular or extreme wave action.

1. Introduction

In the past few decades wave structure interaction including, amongst other things, wave generation and absorption, wave slamming, green water overtopping and floating structures has been widely studied both experimentally and numerically within the coastal and offshore engineering community (Faltinsen et al., 2004; Chen et al., 2014b; Gao et al., 2014; Oliveira et al., 2012; Zhao and Hu, 2012). In particular, floating structures as well as their response under wave actions are of great interest (Koo and Kim, 2004; Hadžić et al., 2005; Zhao and Hu, 2012; Bouscasse et al., 2013; Weller et al., 2013; Zhao et al., 2014). This paper focuses on developing a strong coupling algorithm for the investigation of two-way fluid–solid interactions with an emphasis on floating bodies. This algorithm involves two major issues: a Cartesian cut cell based technique for solid boundary representation and a strong coupling scheme for two-way fluid–solid interactions. Both issues

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are introduced followed by a brief description of the full particle PIC based numerical model PICIN (Kelly et al., 2015), which is employed as a framework for the proposed strong fluid–solid coupling approach in this paper.

Numerically, various models have been proposed for representing solid boundaries and simulating fluid–solid interactions. Focusing on Eulerian methods we highlight the immersed boundary (IB) technique (Peskin, 1972, 2002), which transfers solid boundary effect to a force field on the fluid grid. However, this approach may cause the fluid to permeate structures as mentioned in Batty et al. (2007). Glowinski et al. (1999) and Patankar (2001) proposed the Distributed Lagrange Multiplier (DLM) method for particulate flows. This approach is straightforward to implement and has previously been extended for use in the PICIN model. Nevertheless, the DLM method may have limitations in simulating surface-piercing floating bodies within the current PICIN model as discussed below. Batty et al. (2007) introduced the variational framework for the solution of pressure in fluid flow for fluid–solid interactions, and demonstrated that this method can be easily coupled with freely moving solids of arbitrary geometry. However, Ng et al. (2009) argue that the variational approach is not convergent in the L^{∞} norm for problems involving fixed structures and thus not suitable for computations where velocity field around objects is important; instead, they proposed a novel and more accurate Cartesian cut cell method for simulating fluid interacting with fixed and motion prescribed solids. The so-called Cartesian cut cell approach has been widely used as an alternative approach to unstructured grids for structures with complex body shapes (Noh, 1963; Purvis and Burkhalter, 1979; Quirk, 1994; Ye et al., 1999); it offers great advantages when moving boundaries are employed since there is no need to re-mesh the computational grid (Yang et al., 2000; Qian et al., 2006; Ng et al., 2009). In the context of inviscid compressible flow Noh (1963) first suggested combining the idea of a cut cell fraction with an application of the finite volume method to treat (deformable) solid boundaries. A similar approach was also proposed by Purvis and Burkhalter (1979) to solve the equations of transonic potential flow. This procedure was then further investigated by Ng et al. (2009) with regard to the order of convergence and accuracy; results from Ng et al. (2009) show a second-order accuracy in both the L^1 and L^{∞} norms in 2D. In this paper, we follow the cut cell approach of Ng et al. (2009) for its high accuracy in resolving fluid–solid interactions and simplicity in handling moving boundaries. We show that it is straightforward to implement this approach in PICIN and it is convergent in the L^2 norm in 2D when the grid is sufficiently fine. The detailed description of this cut cell approach is given in Section 2.

In a coupled fluid–solid system, when the influence from one aspect to another becomes negligible, an one-way coupling will work well, e.g. the simulation of a piston type wavemaker (Chen et al., Unpublished results). In most cases, however, both the solid and the fluid phase interact with each other and two-way fluid–solid coupling is required, e.g. Hadžić et al. (2005), Batty et al. (2007), Zhao et al. (2014), and Kelly et al. (2015). Among those schemes, when solid structures are only used to provide velocity boundaries for the solution in the fluid domain and the fluid is solely employed to give a pressure boundary for solid computations, they are usually termed as weak coupling (e.g. Hadžić et al., 2005; Zhao et al., 2014). In this sense, strong coupling is defined to mean that the effects of fluid and solid boundaries are treated simultaneously. Typical examples of strong coupling schemes can be found in Patankar et al. (2000), Batty et al. (2007), and Kelly et al. (2015). The PICIN model is currently only suitable for incompressible fluids. Within this framework, we found that when implementing a weak coupling scheme, especially for studies of wave and floating structure interactions, the behaviour of pressure in the fluid domain can be very stiff which causes instabilities in both fluid and solid motion calculations. The main reason for this is that the fluid pressure is used not only to update the solid domain but also to maintain the flow incompressibility in the PICIN solver; therefore, an inaccurate value for the velocity change on the solid boundaries will cause large pressure fluctuations inside the fluid phase which in turn exerts an incorrect force on the structure and can ultimately cause the numerical model to fail. This type of stiff pressure behaviour in algorithms for incompressible flow has been discussed previously by Fedkiw (2002). Although this unstable pressure behaviour can be potentially alleviated by iterating the solver to a convergent state (e.g. Hadžić et al., 2005; Borazjani et al., 2008), the CPU cost is, in many cases, prohibitively expensive. Thus, strong fluid–solid coupling schemes are the preferred approach to be adopted in the PICIN model. The model previously used a modified version of the DLM method of Patankar et al. (2000) for fluid–solid interactions. The solids are treated exactly as fluids at first and then a velocity correction within the solid phase is made due to the density differences and a rigidity constraint. This method is efficient and has been applied for coastal flows in a previous study (Chen et al., Unpublished results). However, since in this approach the solids are treated as fluids in the initial stages, the surface-piercing portion of a rigid floating body needs to be treated as the free surface of the fluid. It is necessary, and non-trivial, to consistently apply the boundary conditions, especially in the presence of angled corners such as floating boxes. The DLM approach thus requires further validation and improvements within the PICIN model when it is to be used for simulating surface-piercing floating structures for engineering applications. Instead, in this paper, we focus on the strong coupling approach presented by Batty et al. (2007), where the fluid pressure in cells immediately surrounding the solid body are connected together and implicitly solved within a variational framework. Here we combine this implicit approach to the fluid solid motion with the cut cell based solid boundary representation of Ng et al. (2009) instead, within the PICIN model framework. We show that this new approach enables our model to simulate floating body cases in a stable and efficient manner.

The PICIN model is a full particle Particle-In-Cell solver (Brackbill and Ruppel, 1986; Zhu and Bridson, 2005; Kelly, 2012) for incompressible free-surface flows and is especially designed for coastal and offshore engineering applications. As a hybrid Eulerian–Lagrangian approach, the PICIN model has both the flexibility of a Lagrangian approach in terms of simulating complex free-surface flow and the efficiency of an Eulerian approach. The model adopts the pressure projection technique first proposed by Chorin (1968) for the solution of incompressible Newtonian Navier–Stokes equations.