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Interaction of two-phase flow with animated models

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Abstract

In the present work we propose a simple and flexible fluid simulation method that enables us to perform one-way interactions of animated bodies with a coupled gas–liquid flow. This way we can animate flows in which not only the liquid but also the air is a performer. Our method allows the use of rigidly moving, articulated or deforming meshes. The paper shows how to do this practically, using a coupled level set and volume-of-fluid method. We also introduce to computer graphics a novel boundary condition, useful for open-field simulations. Animations of a swimmer in a pool, a hand scooping out water and a heart beating and spurting out either liquid or gas, showcase the strengths of our method.

Keywords: Level sets; CLSVOF; Fluid–structure interaction; Multiphase flow

1. Introduction

As the animation and special effects industries grow in sophistication (as a consequence of the constant need for more realism or versatility), the subfield of fluid animation experiences itself an expansion of its boundaries and capabilities. The present paper addresses a specific problem that derives from the aforementioned expansion of capabilities. Namely, it is common now in fluid animation to have an animated character interacting with a body of *liquid* (see for example Foster and Fedkiw [8]), but more research is needed in order to obtain good interaction with a coupled *gas–liquid* flow. In the present work we propose a novel physics-based method that enables us to provide an automatic solution for such interactions, in which *both* the liquid and the air act as performers. Our paper outlines the practical aspects of this approach, in a coupled level set and volume-of-fluid setting. The contribution of our work consists in offering a simple and powerful automatic solution to the problem in question, thus avoiding non-physical approximations in which air-bubbles are modeled separately from the liquid flow.

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Our approach is geared towards the needs of animators working in the movie industry. A common scenario in a production setting is for the animator to receive a sequence of moving meshes, and be asked to have them interact with a body of water or other liquid, or with a multiphase flow (e.g. water + air). The methods of choice in the last decade for simulating fluids have been Eulerian, and we follow the trend, with a two-phase flow simulator that uses a coupled level set and volume of fluid method for surface advection. Our system consists thus of two components, the aforementioned fluid simulator and a component that handles the interaction with the moving meshes, interpolating (at each time step) the animated mesh surface and velocity from the Lagrangian grid to the Eulerian grid.

Regarding the fluid simulator, we use the two-phase flow version of the coupled level set and volume-of-fluid (CLSVOF) method of Sussman et al. [35]. This method has been used in a simpler setting (only one phase/fluid) by Mihalef et al. [25] to generate and control breaking ocean waves, and in its present form by Mihalef et al. [26] to generate boiling flows. In this work we extend the method in order to handle interaction with pre-animated models, which dictate velocity boundary conditions for the gas/liquid flow. The CLSVOF method combines a level set ingredient for generating smooth surfaces and a volume-of-fluid ingredient that improves the mass conservation properties of the level set solver. While other methods like Hong and Kim [17] or Mihalef et al. [26] generated bubbly water flow interacting with fixed objects, we go one step further in functionality, showing interactions with prescribed complex object motion. We also point out that our method is physics-based, whereas the methodology used by Hong and Kim [17] features a non-physical approximation of the variable-density projection equation for pressure (Eq. (5) in their paper). In Jimenez et al. [22] our numerical model is compared favorably with experimental photographs of *real* bubbles. There has been work on interaction with moving meshes, such as Carlson et al. [3], Guendelman et al. [15], and Chentanez et al. [2], where only one-phase water flow is used, but two-way interactions are shown as well. We note also that Kim et al. [20] and Carlson et al. [3] report fluid interaction with solids that undergo only rigid body motion. In fact, Kim et al. [20] present a two-phase flow system in the same vein with ours, but developed in a different direction. Their system handles two-way interactions, but they do not focus, like us, on simulations in which the solid performs very complex prescribed motion, as is usually the case in animation.

Another feature of our paper is the introduction to graphics of a boundary condition model suitable for open-field simulations, like the ones encountered for example by a character swimming in the ocean. A common practice for such a case is to choose the domain large enough so that the walls (enforcing Dirichlet boundary conditions) do not make their influence sensed, but such an approach is obviously inefficient. A choice of Neumann boundary conditions would inevitably drain the domain. We counter that by enforcing special hydrostatic pressure conditions along the vertical boundaries. These boundary conditions are cast as body forces into a novel version of the Navier–Stokes solver, ensuring that no extra computational algorithm needs to be implemented for the pressure solver. This approach has been used in the computational fluid dynamics community before, see for example Dommermuth et al. [4].

Our paper also introduces a new algorithm for computing the level set map for a mesh. Our algorithm, described in Section 3.1, uses a multigrid-like approach and is more efficient than standard methods like the one proposed by Mauch [24].

In summary, our paper proposes a physics-based system that handles interactions of Eulerian *two-phase flow* with complex animated meshes, in a manner that is algorithmically simple yet versatile enough for an animator's needs. As far as the authors are aware, this is the first paper to show this type of interaction of deforming animated meshes with coupled air/water flow in an Eulerian setting (recall that Foster and Fedkiw [8] and Guendelman et al. [15] showed only interaction with one-phase flow, while Kim et al. [20] only showed interaction of two-phase flow with a rigid body). It also introduces to graphics a useful method for modeling open-field boundary conditions and an efficient algorithm for generating a level set corresponding to a closed mesh. As we show in our examples, this type of one-way interaction between animated meshes and coupled air–water flow that we tackle in our paper leads to very complex, novel and useful animations.

The following section of the paper reviews previous work related to ours, concerning Navier–Stokes solvers and interactions between solid objects and liquids. Our simulation method is presented in Section 3, followed by several illustrative animations in Section 4. The final part contains concluding remarks, as well as an overview of the directions that our future research will follow.