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The effect of air on solid body impact with water in two dimensions

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ABSTRACT

In this paper we study the motion of wedge and catamaran shaped hulls initially in air, then impacting with water. We consider motion in two dimensions and simulate the impact using SPH in a form suitable for two-phase flow. This SPH algorithm has been tested for a variety of problems involving air and water with very good results. However, we supplement those tests by simulating the dynamics of bubbles, and the motion of piston driven by the pressure of air in a tube. The former confirms that our algorithm simulates the motion of two fluids with a high density ratio (in this case 1000) while the latter is relevant to the impact of a catamaran shaped hull where the trapped air cushions the impact. In both cases the results are in very good agreement with theory. When applied to simulate the dynamics of a wedge falling into a fluid the results are in good agreement with theory and confirm that the effect of the air on the motion is small because the air can escape easily as the wedge enters the water. When applied to simulate a model catamaran hull in two dimensions, where the air is trapped beneath the hull, the effect of air is pronounced. The simulations with the catamaran hull are not in close agreement with experiments because the hull in three dimensions does not trap air effectively as it does in two dimensions.

1. Introduction

The details of the dynamics of a body impacting a fluid are required to estimate the stresses on ship hulls, or on the floats of sea planes, or to estimate the breakup of an aircraft when it crashes into a body of water. This impact is called slamming and the review by Kapsenberg (2011) shows examples where it can lead to the fracture of a ship's hull. The analysis of slamming was initiated by Von Karman (1929) who estimated the force on the floats of sea planes from the change in the added mass. Wagner (1932) used potential theory to make detailed calculations of the pressure and the velocity field produced by a wedge moving at constant speed into initially static water. A review of the early analytical methods is given by Korobkin and Pukhnachov (1988) and later work is discussed in the review by Kapsenberg (2011). The weakness with the analytical or semi-analytical methods is that their application is restricted to simple shapes, and to flows where viscosity can be safely neglected, and to hull shapes that do not produce air pockets that cushion the impact. Experiments such as those of Okada and Sumi (2000) indicate that air cushions the impact of flat plates when the plate is at a small angle, less than

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$\sim 3^{\circ}$. Similar results were obtained by Lind et al. (2013, 2015). In related work Shahraki et al. (2011) describe experiments on a simplified catamaran hull that shows how air can cushion the impact.

Although our ultimate aim is to simulate the impact problem in three dimensions we consider motion in two dimensions in this paper since it is then easier to establish that the algorithms are effective, and many aspects of the physics of impact are similar in two and three dimensions. Nevertheless, aspects of the flow are different because air can escape from under the hull more easily in three dimensions and, as a consequence, the air cushions the impact more strongly in two dimensions. This must be kept in mind when interpreting our results. We use both wedge and catamaran hulls choosing, in the latter case, a hull shape that prevents the air beneath the hull escaping.

Our computational method is SPH (for reviews see Monaghan, 1992, 2005, 2012). The dynamics of a wedge in two dimensions falling under gravity or with a constant velocity, and in the absence of air, has been calculated by Oger et al. (2006) and by Shao (2009) using different forms of the SPH algorithm. The former authors use a weakly compressible algorithm, and variable resolution lengths without consistently including the gradients of the resolution length in the equations of motion. Shao (2009) treats the liquid as incompressible with constant resolution length. The results are in reasonable agreement with the experiments of Zhao et al. (1997) (see Oger et al., 2006, Figs. 9 and 10, and Shao, 2009). The effect of air in these experiments is small because the angle of the wedge face to the water surface is large, typically 25°. The only SPH calculation that simulates impacts that include air and water that we are aware of is that of Lind et al. (2013, 2015) who model the impact of a flat plate. The system was simulated with an incompressible model for the water and an adiabatic equation of state for the air.

Our version of the SPH algorithm is based on the work of Monaghan and Rafiee (2012) who simulated two phase flows with high density ratios. This method has been tested on several demanding problems including the motion of oscillating cylinders with a low density outer layer around a high density inner layer, oscillations of the interface of a 2-layer stratified tank, the Rayleigh Taylor instability, and gravity currents. The plan of this paper is to implement further tests that are relevant to the impact problem then, having established the accuracy of our code, to apply it to the impact problem. The first of these tests is the rise of a bubble in a fluid under gravity which tests the motion of air in a denser fluid. The second determines how well the dynamics of a solid–fluid interface is simulated, and this is achieved by simulating a piston oscillating in a tube containing air. The results of these tests establish that the algorithm gives good results for the motion of fluids in the presence of moving solid bodies. We then apply our code to the impact of wedge and catamaran shaped hulls. In the case of the wedge we compare our results against theory and find good agreement. As expected the inclusion of air has only a small effect because it is not trapped by the wedge, but it is useful to confirm that our simulation of a solid wedge passing through air to enter water is well behaved. The simulation of the catamaran hull shows that our algorithm can handle a complicated body and predict the effect of trapped air. Our results do not agree well with experiments for the following reasons: the experiments are in three dimensions and the air can escape easily, and the beam width is twice the length so that end effects are significant. Nevertheless our results establish that our algorithm can handle a situation where air, trapped by the hull, results in rapid deceleration.

2. Lagrangian based SPH equations

We consider a system consisting of two or more fluids, which may be liquids or gases in which there is a moving rigid body. We assume that the pressure in each case can be found from an internal energy u which may have a different functional form for each fluid, and we neglect the effects of surface tension. For the present we assume that rigid boundaries which include the walls of the tank and the boundaries of the moving rigid bodies are defined by boundary force SPH particles (Monaghan and Kajtar, 2009). The reader may refer to standard SPH as described in the reviews by Monaghan (1992, 2005).

We use the SPH equations of motion derived from a Lagrangian by Monaghan and Rafiee (2012). The appropriate continuity equation best suited to problems involving fluids with very different densities is

$$\frac{d\rho_b}{dt} = -\rho_b \sum_\eta \frac{m_\eta}{\rho_\eta} (\mathbf{v}_\eta - \mathbf{v}_b) \cdot \nabla_b W_{b\eta}, \tag{2.1}$$

where the summation is over all particles. Here m_b, ρ_b, $\mathbf{v}_b$ and $\mathbf{r}_b$ are, respectively, the mass, density, velocity and coordinate of particle b. We include boundary force particles in this summation because they contribute information about the velocity of the boundary. Furthermore, the combination m_η/ρ_η is invariant to changing the mass of the contributing particles provided their densities are changed consistently. The SPH estimate of $\nabla \cdot \mathbf{v}$ is therefore invariant to such a change in the fluid, and only depends on the local velocity field as it should. The function $W_{b\eta} = W(|\mathbf{r}_{b\eta}|, h)$, with the notation $\mathbf{r}_{b\eta} = \mathbf{r}_b - \mathbf{r}_\eta$, is the SPH kernel (see below), and ∇_b denotes the gradient taken with respect to the coordinates of particle b. The continuity equation for all particles (except the boundary force particles which have constant density) is the same. The continuity equation is used as a constraint on the Lagrangian variations which lead to the acceleration equation

$$\frac{d\mathbf{v}_a}{dt} = -\sum_\eta m_\eta \left(\frac{P_a + P_\eta}{\rho_a \rho_\eta} + R_{a\eta} + \Pi_{a\eta} \right) \nabla_a W_{a\eta} + \sum_j m_j \mathbf{r}_{aj} f(|\mathbf{r}_{aj}|) + \mathbf{g}, \tag{2.2}$$