High-speed water impacts of flat plates in different ditching configuration through a Riemann-ALE SPH model

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Abstract: The violent water entry of flat plates is investigated using a Riemann-arbitrary Eulerian-Lagrangian (ALE) smoothed particle hydrodynamics (SPH) model. The test conditions are of interest for problems related to aircraft and helicopter emergency landing in water. Three main parameters are considered: the horizontal velocity, the approach angle (i.e., vertical to horizontal velocity ratio) and the pitch angle, α. Regarding the latter, small angles are considered in this study. As described in the theoretical work by Zhao and Faltinsen (1993), for small α a very thin, high-speed jet of water is formed, and the time-spatial gradients of the pressure field are extremely high. These test conditions are very challenging for numerical solvers. In the present study an enhanced SPH model is firstly tested on a purely vertical impact with a deadrise angle α = 4°. An in-depth validation against analytical solutions and experimental results is carried out, highlighting the several critical aspects of the numerical modelling of this kind of flow, especially when pressure peaks are to be captured. A discussion on the main difficulties when comparing to model scale experiments is also provided. Then, the more realistic case of a plate with both horizontal and vertical velocity components is discussed and compared to ditching experiments recently carried out at CNR-INSEAN. In the latter case both 2-D and 3-D simulations are considered and the importance of 3-D effects on the pressure peak is discussed for α = 4° and α = 10°.

Key words: Aircraft ditching, high-speed water entry, smoothed particle hydrodynamics (SPH)

Introduction

The problem of the high-speed water entry is classically of interest in the naval field as far as slamming loads on ships are concerned. In this context several theoretical solutions have been derived for simplified conditions and a large literature of experimental data is available. Water-entry problems are also very important in the aircraft ditching, that is, the emergency landing on water. The response of the vehicle to this kind of water impact is critical in terms of safety of the passengers and certifications issued by airworthiness authorities includes the success of the airframe in ditching tests. In this context few high-fidelity numerical methods have been developed so far[1,2].

The smoothed particle hydrodynamics (SPH) method has already shown promising results for the simulation of violent water impacts thanks to its accuracy and easiness in following the free-surface deformations[3-5]. In the present work an in-depth study and validation of the SPH model is provided for 2-D water entries of flat panels with small deadrise angle. Both purely vertical and oblique impact velocity with high horizontal velocity component are studied (Sections 2 and 3). These conditions are of interest for, respectively, helicopter and airplane ditching situations. To this aim the numerical outcome will be compared to experimental measurements and analytical solutions when available. The influence of the 3-D effects are also addressed for the oblique water entry through a 3-D SPH solver. In order to accurately resolve the high and localized pressure peaks developed at the impact a Riemann-based SPH solver is used within an arbitrary Eulerian-Lagrangian (ALE) framework. The choice of the numerical parameters to be adopted, as e.g., the liquid compressibility, is critically and extensively discussed on the base of physical considerations peculiar of water-
impact flows.

1. Adopted SPH scheme

In the present work Euler equations for compressible fluids are solved. Indeed, since the Reynolds number of the flow is quite high and only the impact stage is simulated (short time-range regime) viscous effects can be considered negligible. The weakly-compressible model is adopted, the fluid is, therefore, assumed to be barotropic and a classical stiffened state equation is used

\[ p(\rho) = \frac{c_s^2 \rho_0}{\gamma} \left[ \left( \frac{\rho}{\rho_0} \right)^\gamma - 1 \right] + p_0 \]  

(1)

where \( \rho_0 \) and \( p_0 \) are constant, \( c_s \) is the speed of sound, and \( \gamma \) is a dimensionless parameter greater than 1 (in all of the following examples \( \gamma = 7 \) is used).

When considering violent free-surface flows, the proper identification of the reference velocity \( U_{ref} \) is crucial, as discussed in the following sections. Considering the Mach number \( Ma = U_{ref} / c_s \), the constraint \( Ma < 0.1 \) is enforced to make compressibility effects negligible. Additionally, during violent impact events (i.e., flat impacts) the acoustic pressure \( p = puc_0 \) can be reached, and in this case the pressure peak intensity becomes proportional to \( 1/Ma \). On the other hand, in such a condition an incompressible constraint can induce singularities on the pressure field (see Ref. [6] for a discussion on the difference between these two models in impact situations). This is linked to the fact that for this kind of impacts the presence of the air phase is generally crucial and the single-phase approach can lead to incorrect pressure evaluations under the incompressible/weakly-compressible hypothesis (for a deeper discussion see also Ref. [4]). Being aware of these limits of the single-phase model, the results obtained in this paper have been produced considering a possible Mach dependency.

In the present work the Riemann-based solver described in Ref. [7] is adopted. In that work the ALE formalism is used allowing for maintaining a regular particle spatial distribution and smooth pressure fields while preserving the whole scheme conservation and consistency of the classical SPH scheme. The introduction of the Riemann-based solver in the SPH scheme leads to an increased stability and robustness of the scheme with respect to the standard SPH formulation. The formalism proposed by Ref. [8], Thanks to the introduction of Riemann-solvers the fluxes between particles are upwind oriented and the resulting scheme is characterized by good stability properties. The discrete Euler equations are written as follows:

\[ \frac{D\rho}{Dt} = \nabla \cdot \mathbf{v}_i \]  \hspace{1cm} (2a)

\[ \frac{D\mathbf{v}_i}{Dt} = \frac{1}{\rho_i} \left( \mathbf{v}_i \cdot \nabla \right) \rho_i + \frac{1}{\rho_i} \left( \frac{1}{2} \frac{\partial E_i}{\partial \mathbf{v}_i} - \frac{1}{2} \frac{\partial E_i}{\partial \mathbf{v}_j} \right) \mathbf{v}_j \]  \hspace{1cm} (2b)

\[ \frac{D(\rho_i \mathbf{v}_i)}{Dt} = \nabla \cdot \left( \mathbf{v}_i \otimes \rho_i \mathbf{v}_i \right) + \rho_i \mathbf{g} \]  \hspace{1cm} (2c)

\[ \frac{D(\rho_i \mathbf{v}_j \chi)}{Dt} = \nabla \cdot \left( \mathbf{v}_j \otimes \rho_i \mathbf{v}_i \chi \right) + \rho_i \mathbf{g} \]  \hspace{1cm} (2d)

where \( \rho_i \), \( P_i \) and \( v_i \) are the solutions of the Riemann problem at the interface \( r_j = (r_i - r_j)/2 \), between particles \( i \) and \( j \). The particle transport velocity \( \mathbf{v}_i \) is obtained as the summation of the particle velocity plus a small perturbation which helps to preserve a regular particle distribution (details about the adopted model can be found in Ref. [7]).

2. Vertical water entry of a flat panel

In this first section the vertical impact of a flat plate is numerically investigated and validated. Specifically, results of the 2-D single-phase simulations are described and compared to the experimental data from a wet drop test performed in Ref. [9]. In that work a flat panel (panel length \( L \) equal to 0.64 m) impacting with a deadrise angle of \( 4^\circ \) and a vertical impact velocity \( U \) of 6.0 m/s is studied. Measures of pressures at several positions along the plate are taken, allowing for a detailed control of the pressure peak repeatability and for possible 3-D effects.

As described in the theoretical work by Ref. [10], for these small deadrise angles a very thin, high-speed jet of water is formed, and the time-spatial gradients of the pressure field are extremely high. This makes the test conditions very demanding for numerical solvers. From the potential flow theory by Ref. [10], the jet thickness at model scale is about 0.1 mm. It is worth noting that the theory in Ref. [10] is formulated for symmetric wedge impacts whereas in the present case the impact of an inclined single plate is considered. More details about the reference solution to be adopted are given in Section 2.2.