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Numerical predictions of water–air wave slam using incompressible–compressible smoothed particle hydrodynamics

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ABSTRACT

The high-speed impact between a body and water is an important practical problem, whether due to wave impact on a structural deck or wall, or due to a moving body such as a ship or aircraft hitting water. The very high pressures exerted are difficult to predict and the role of air may be significant. In this paper, numerical simulations are undertaken to investigate the impact of a rigid horizontal plate onto a wave crest and, in the limit, onto a flat water surface. A two-phase incompressible–compressible smoothed particle hydrodynamics (SPH) method for water and air, respectively, is applied where the water phase imposes kinematics on the air phase at the air–water interface and the air phase imposes pressures on the water at the interface. Results are compared with experimental measurements undertaken using a drop rig positioned over a wave flume so that a horizontal plate impacts the water surface in free flight. Numerical predictions of impact pressure are quite accurate; air is shown to have a significant cushioning effect for impact on to flat water and this reduces for waves as the ratio of wave height to wavelength increases.

1. Introduction

Slam loads on offshore structures due to waves have long been a problem of great practical importance for the oil and gas industry. Structures are now also being deployed to support wind turbines in coastal waters and provide substations for connection to the electricity grid; here slam loads occur on the structure legs and on the underside of a deck. The impact loads due to slam on the underside of high-speed craft and during aircraft ditching are equivalent hydrodynamic problems. The magnitude of the almost impulsive impact pressure is particularly uncertain and difficult to predict. Impacts are anecdotally associated with loud bangs indicating that the air phase may be significant.

Von Karman [43] made some of the first theoretical insights into slam problems for application to seaplane landings; assuming a single-phase, incompressible, inviscid flow and neglecting gravity, he considered a circular cylinder to be an expanding flat plate with the water surface remaining flat. Wagner [44] extended this to the 2-D wedge entry problem, including a local analysis of jet structures. The fundamental problem of a flat plate hitting still water has since been studied experimentally by a number of authors over several decades. Early work included investigations by Chuang [4], Lewison and Maclean [18], Verhagen [42], Miyamoto and Tanizawa [27] and Lin and Shieh [19]. These papers demonstrated the importance of the air phase during impact, especially its ability to reduce impact pressures and also deform the water surface before body contact. It was the pioneering experimental work of Chuang [4] that first demonstrated the significantly reduced impact pressures compared to classical Wagner theory. Verhagen [42] undertook similar experimental work on horizontal flat plate slam, but also offered a theoretical 1-D model for the effect of the trapped air cushion. Lewison and Maclean [18] noted that, provided the deadrise angle is small enough, air can be forced into the water phase during impact, suggesting a coalescence of water and vapour, and the dissolution and entrainment of non-condensible gases. In the experiments of Lin and Shieh [19], a trapped air-layer was found to persist beneath the plate post impact, resulting in a uniform pressure distribution in the central region of the impacting surface but a very complex bubbly flow at the periphery. These post-impact flow structures were also noted by Miyamoto and Tanizawa [27]. A more recent study by Okada and Sumi [34] categorised the impacts observed from their experiments on free falling plates at small impact angles. For very small impact angles they noted smooth impact pressure distributions (spread almost uniformly across the plate) due to the cushioning effect of trapped air. For angles greater than 4°, they observed “Wagner-type” impacts characterised by larger, sharper pressure peaks (in both space and time). Okada and Sumi [34] also noted a transition region (between 1° and 3°) where both Wagner and trapped-air pressure distributions can occur over the course of the impact event. Typically, Wagner-type pressures are observed

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under the base, while trapped-air pressure patterns are observed near the plate edges. It is noted that the peak pressures measured in this transition region are highly scattered. Recently, Huera-Huarte et al. [13] have undertaken experimental investigations into the slamming forces on flat sandwich panels impacting a free surface at a variety of impact speeds and angles. A good agreement with asymptotic theory, e.g. Zhao and Faltinsen [48], was found for large impact angles, but, at small angles, the theory considerably overestimated the loading forces due to the increasing influence of trapped air.

The extreme characteristics of slam pose considerable modelling challenges, and, consequently, many numerical studies have focused on the dynamics some time after the initial violent impact, where the flow features (such as jet formation) evolve over longer time scales. For example, with regard to general impact and slam problems, a seminal paper by Greenhow [10] was the first to embark upon a numerical potential flow solution of wedge entry, with a good qualitative agreement with experiment being found post-impact. Ng and Kot [31] considered flat plate slam using a volume-of-fluid numerical method, and included the influence of air (which they assumed to be incompressible). The importance of the air phase was noted in its ability to deform the water surface prior to impact, but there was an admission that the cases studied were somewhat idealised and not directly comparable with experimental data. Furthermore, no results were presented beyond the point of water contact. Iwanowski et al. [14] undertook a similar numerical investigation into horizontal rigid body impact, including the effect of a compressible air cushion. The governing equations for air and water (modelled as compressible and incompressible fluids, respectively) were solved on a time-varying mesh using finite-differences and the volume-of-fluid (VOF) method. As in Ng and Kot [31], deformations in the water surface and the air pressure exerted on the body could be predicted in the moments up to water-body impact. More recently, Yang and Qiu [47] used a constrained interpolation profile (CIP) finite-difference method to look at a number of slam problems, including flat plate slam. By transforming the general conservation of mass equation into a Helmholtz equation for the pressure, their approach allowed both air and water phases to be accurately modelled, including the effect of water compressibility. The impact pressure predictions for flat plate slam were found to be in good agreement with the experimental work of Verhagen [42], although slightly different entry conditions were imposed.

In recent years, the Lagrangian smoothed particle hydrodynamics (SPH) method has shown a great deal of promise over other, more traditional, grid-based numerical methods when modelling violent impact problems. The Lagrangian particle nature of SPH means that highly deforming flows undergoing severe topology change are captured automatically, enabling all aspects of the slam event to be described (before, during and long after impact). Consequently, SPH has been utilised by a number of investigators to gain further insights into impact problems. Gao et al. [7] investigated wave slam onto the underside of a deck using a Riemann-enhanced single-phase SPH formulation. Their predictions for the impact pressures on the deck were in reasonable quantitative agreement with experiment. Oger et al. [32] undertook a numerical study of wedge-entry problems using a variable smoothing length SPH method. Their results were in good agreement with experimental and analytical results for a number of important measures, including accelerations and pressures. However, they noted that the greatest discrepancies with experiment occur at the very start of the impact as air cushion effects were not modelled in their formulation. Shao [38] used an incompressible SPH formulation, accompanied by an LES-type turbulence model, to study free-falling wedge entry problems. The results for the forces on the wedge (after the initial impact) were in agreement with experimental and theoretical predictions. Recently, Skillen et al. [40] developed an improved single-phase incompressible SPH method (based on the projection approach enforcing zero divergence), and investigated some classical wedge and cylinder slam problems. By employing a shifting algorithm similar to that developed in Lind et al. [20] (which itself is based on the shifting methodology of Xu et al. [46]), the approach of Skillen et al. [40] incorporated a smoothed pressure boundary condition at the free-surface, which resulted in good quantitative agreement with analytical and experimental measurements of loads after the initial impact.

As discussed, the role of air in the slam process is thought to be important in determining the pressure and local forces generated at impact. Experimental findings (e.g. Okada and Sumi [34]) generally show that trapped air helps to cushion the impact and reduce impact pressures. In the case when air is not trapped at the surface but entrained in the water, a theoretical analysis by Peregrine and Thais [35] indicates that impact pressures can be reduced by an order of magnitude. In the majority of numerical investigations (including the aforementioned SPH studies), the influence of the air phase is often neglected. As pointed out in Oger et al. [32], this produces disagreement with experimental results in the early stages of impact and it is in these early stages that the most violent and potentially damaging peak pressures occur. In this paper an improved understanding of the slam process, particularly the role of the air cushion, is obtained through the numerical modelling of rigid flat plate impact using a state-of-the-art two-phase SPH method. The incompressible–compressible (water–air) two-phase SPH method (ICSPH) is applied which combines a compressible air phase with a truly incompressible water phase, thereby providing a physically accurate description of both fluids. It has been demonstrated by a number of authors that single-phase incompressible SPH can provide accurate pressure predictions for a wide range of relevant internal and free-surface incompressible flows, including wave propagation [20], water entry problems [40], sloshing [9], and wave run-up with impact [11]. It is, therefore, the most suitable of current state-of-the-art SPH methods to predict the all-important pressures at water-body contact. With regard to including the second (air) phase, two-phase SPH methods are now well-developed, but are usually based on traditional weakly compressible SPH only (see for example [29] and [5]) or purely incompressible formulations (see for example [12] and related work using the MPS method [15]). While water may remain incompressible, the severity of wave slam requires a compressible air phase, because, as we shall see, air ejection velocities prior to impact can approach the speed of sound. In a similar manner to Yang and Qiu [47], Khayyer et al. [16] utilise a fully projection-based particle method to solve compressible–incompressible flows, and good results are achieved for a number of test cases, including 2D liquid impact. However the conditions at the interface are diffusive to some degree as the density discontinuity is necessarily smoothed. In this paper we impose kinematics from the incompressible phase with pressure from the compressible phase at the interface, which enables a physical material discontinuity to be maintained at the interface, with the correct step-change in density. The compressible phase is computed in a conventional explicit manner governed by an equation of state (EOS).

It should be mentioned that while the air phase has a demonstrated influence in many water-body impact problems (e.g. Okada and Sumi [34]), gravity and surface tension effects can often be neglected in the modelling to a good approximation (see the classical impact studies of Zhao and Faltinsen [48], Greenhow [10], for example). The impact event is highly inertial, with flow accelerations dominating both gravity and surface tension terms at impact. Both gravity and surface tension can play a role long after impact, especially in the dynamics of well-developed jets, however this is not the focus of this work.