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Three-dimensional water entry of a solid body: A computational study

Andrea L. Facci [a,*], Maurizio Porfiri [b], Stefano Ubertini [a]

[a] DEIM - School of Engineering, University of Tuscia, 01100 Viterbo, Italy
[b] Department of Mechanical and Aerospace Engineering, New York University Tandon School of Engineering, Brooklyn, NY 11201, USA

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ABSTRACT

Marine vessels are continuously subject to impulsive loading from impact on the water surface. Understanding and quantifying the hydrodynamics generated by the three-dimensional (3D) water impact of a solid body is central to the design of resilient and performing vessels. Computational fluid dynamics (CFD) constitutes a viable tool for the study of water entry problems, which may overcome some of the drawbacks associated with semi-analytical and experimental methods. Here, we present a new computational study of the 3D water entry of a solid body with multiple curvatures. The method of finite volume is utilized to discretize incompressible Navier-Stokes equations in both air and water, and the method of volume of fluid is employed to describe the resulting free-surface multiphase flow. Computational results are validated against available experimental findings obtained using particle image velocimetry in terms of both the flow kinetics and kinematics. Specifically, we demonstrate the accuracy of our CFD solution in predicting the overall force experienced by the hull, the pile-up phenomenon, the velocity field in the water, the distribution of the hydrodynamic loading, and the energy transfer during the impact. Our approach is expected to aid in the validation of new semi-analytical solutions and to offer a viable means for conducting parametric studies and design optimization on marine vessels.

1. Introduction

Understanding the hydrodynamics associated with entry of solid bodies into the water surface is pivotal to the design of marine vessels (Abrate, 2013; Faltinsen, 1993; Korobkin, 1996) and aerospace structures (Seddon and Moatamedi, 2006). Just as hull slamming determines the hydrodynamic stability of the vessels during sailing and maneuvering, it influences their structural lifetime (Faltinsen et al., 2004; Hughes et al., 2013; McCue, 2012). Hull slamming results into complex, three-dimensional (3D) impulsive loading, whose spatial distribution and temporal evolution are both sensitive to the geometry of the vessels and their operating speed (Abrate, 2013; Faltinsen, 1993; Hughes et al., 2013; Korobkin, 1996; Seddon and Moatamedi, 2006; Faltinsen et al., 2004; McCue, 2012). Notwithstanding the central role of the hull geometry, most of the technical literature has focused on two-dimensional (2D) water entry problems (Abrate, 2013).

In the realm of 2D approximations, mathematically tractable potential flow solutions have been established to elucidate the hydrodynamics in water entry problems. Building on the seminal work by Wagner on the water entry of solid bodies

* Corresponding author.
E-mail addresses: andrea.facci@unitus.it (A.L. Facci), mporfiri@nyu.edu (M. Porfiri), stefano.ubertini@unitus.it (S. Ubertini).

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with low deadrise angle (Wagner, 1932), significant progress has been made toward dissecting the role of large deadrise angles (Korobkin, 2004; Mei et al., 1999), geometric asymmetries (Judge et al., 2004; Korobkin and Malenica, 2005; Semenov and Iafrati, 2006), and hydroelastic phenomena (Khabakhpasheva and Korobkin, 2013; Panciroli and Porfiri, 2014; Shams and Porfiri, 2015). These efforts have contributed an improved understanding of water impact, isolating the key geometric and physical factors that shape the unsteady fluid–structure interaction. For example, these studies have clarified the mechanics underpinning the formation of a water pile-up in the vicinity of the impacting solid and helped determine the wetted length of the body as a function of its geometry.

These theoretical investigations have been supported by a number of computational models, which have contributed a refined dataset upon which analytical or semi-analytical solutions could be tested and offered further insight into the physics of the impact (Abrate, 2013; Hughes et al., 2013). Several computational schemes have been proposed to study 2D water entry problems, ranging from traditional computational fluid dynamics (CFD) solvers (Colicchio et al., 2006; Das and Batra, 2011; Facci et al., 2015; Luo et al., 2011; Maki et al., 2011; Stenius et al., 2006; Sun and Faltinsen, 2006; Wang et al., 2012; Wang and Soares, 2013a, 2013b) to emerging discrete fluid dynamics methods (De Rosis et al., 2014; Gong et al., 2009; Oger et al., 2006; Shao, 2009; Panciroli et al., 2012; Yang et al., 2012; Zarghami et al., 2014). Different from theoretical treatments based on Wagner solution, computational schemes enable a precise quantification of viscous phenomena along with a refined analysis of the dynamics of the water surface, including the pile-up phenomenon. Their implementation can be easily adjusted to closely simulate experimental conditions, with respect to both the real geometry of the hull and the setup.

In this paper, we seek to advance the field of computational modeling through the study of 3D hydrodynamics generated by the impact of a solid body on the water surface. We consider the complex geometry proposed in Jalalisendi et al. (2015a) to proxy the slamming of a ship hull in a laboratory experimental setting. Specifically, we model the free fall of a solid body whose geometric curvature varies with respect to both its length and width. Our computational scheme builds on our prior work (Facci et al., 2015), where we have established an accurate and versatile CFD toolbox to study the 2D impact of a wedge. Here, we extend such a computational scheme to enable the analysis of 3D water entry, toward a detailed analysis of the pile-up phenomenon, a precise quantification of the hydrodynamic loading experienced by the body on its wetted surface, and a rigorous assessment of the energy transfer during water entry. This extension is motivated by the experimental results in Jalalisendi et al. (2015a), which offer compelling evidence for the importance of 3D phenomena, not captured by 2D approximations, in the impact of ship hulls models with multiple curvatures. Our approach is based on the finite volume method (Patankar, 1980) to discretize the incompressible Navier–Stokes equations in air and water, and the volume of fluid technique to describe the resulting multiphase flow (Rider and Kothe, 1998; Scardovelli and Zaleski, 1999; Rusche, 2003). Different from the finite element analysis presented in Wang and Soares (2014), our framework utilizes an open source software and focuses on a complex hull geometry, with multiple curvatures.

We demonstrate the accuracy of our computational approach through comparison with experimental data from Jalalisendi et al. (2015a), where particle image velocimetry (PIV) is used to measure the 3D flow physics generated by the impact and reconstruct the associated pressure field. PIV is a classical technique in experimental fluid dynamics which uses images of a seeded flow to non-intrusively measure the velocity in the fluid from the motion of the seeding tracers (Raffel et al., 1998). By scanning the flow field in 2D through planar PIV, the methodology proposed in Jalalisendi et al. (2015a, 2015b) affords the systematic measurement of the three components of the velocity vector everywhere in the water. From the knowledge of the 3D velocity field and the identification of both the solid body and the free surface, Navier–Stokes equations can be numerically integrated to estimate the pressure field by extending the approach proposed in Nila et al. (2013), Shams et al. (2015), Panciroli and Porfiri (2013, 2015), and Panciroli et al. (2015) from 2D to 3D.

Contrasting computational findings with PIV results, we provide a thorough validation of our numerical solution, which can aid in the development of new semi-analytical approaches and in the unprecedented quantification of 3D effects. With respect to the use of pressure gauges, accelerometers, and load cells which have been pervasive in experimental studies on water entry (Carcaterra and Ciappi, 2004; Luo et al., 2012; Peterson et al., 1997; Tveitnes et al., 2008; Van Nuffel et al., 2013, 2014; Wu et al., 2004), PIV allows for verifying numerical predictions on both the pressure and velocity everywhere in the water, which would otherwise be not feasible (Wang and Soares, 2014). This knowledge is in turn utilized to quantify the spatial distribution and temporal evolution of the loading experienced by the hull and estimate the energy transfer during the impact. Our experimentally validated computational approach can be effectively used as a valid alternative to more costly and labor-intensive experimental schemes in parametric studies and design optimization.

The rest of the paper is organized as follows. In Section 2, we briefly describe the problem under investigation. In Section 3, we summarize the experimental scheme presented in (Jalalisendi et al., 2015a) and detail our computational approach. In Section 4, we present our main results, which include the prediction of the overall force experienced by the hull, the pile-up dynamics, the water velocity, the hydrodynamic loading, and the energy transfer. Section 5 contains the conclusions of our study and an outlook on future work.

2. Problem statement

The geometry of the specimen is sketched in Fig. 1. Relevant properties, such as the length l, width b, height h, and mass M are reported in Table 1. The deadrise angle β and the curvature R vary in two dimensions (the exact shape of the hull can

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