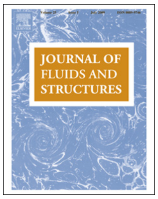
Journal of Fluids and Structures 59 (2015) 85–102

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs



# Three-dimensional water entry of a solid body: A particle image velocimetry study

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ARTICLE INFO

*Article history:*
Received 13 April 2015
Accepted 21 August 2015
Available online 8 October 2015

*Keywords:*
Hydrodynamic loading
Particle image velocimetry
Pile-up
Slamming
Water impact

ABSTRACT

Understanding and predicting the hydrodynamic loading experienced by a solid body during water impact is critical for researchers and practitioners in naval engineering. While two-dimensional (2D) water entry problems have been extensively investigated, experimental data on 3D fluid–structure interactions during water impact are rather limited. Here, particle image velocimetry (PIV) is utilized to study the free fall vertical impact of a solid body, modeling a ship hull, on an otherwise quiescent fluid. Planar PIV is used to measure the velocity field on multiple cross-sections along the length and width of the model. These data are combined to infer the 3D velocity field in the entire fluid. The 3D velocity field is then utilized to reconstruct the pressure field by integrating the incompressible 3D Navier–Stokes equations in a time-varying domain, where both the free surface and the fluid–solid interface evolve in time. By evaluating the pressure field on the wetted surface of the model, we estimate the hydrodynamic loading during water entry. Experimental results demonstrate the central role of 3D effects on both the flow physics and the hydrodynamic loading. As the cross-sectional velocity decreases away from the mid-span, we observe a robust increase in the axial velocity component. This translates into a complex spatio-temporal dependence of the hydrodynamic loading, which is initially maximized in the vicinity of the pile-up and later increases toward the keel. Due to the deceleration of the model during the impact and the increase in the wetted surface, the hydrodynamic loading close to the mid-span in the early stage of the impact is considerably larger than the ends. The 3D flow physics is used to study the energy imparted to the fluid during the impact, which we find to be mostly transferred to the risen water, consisting of the pile-up region and the spray jet. Our methodology can be implemented for the analysis of other solid bodies with multiple geometric curvatures, and our experimental results can be utilized for the validation of 3D mathematical models of water entry.

## 1. Introduction

The characterization of the hydrodynamic loading experienced by solid bodies during water entry is of fundamental importance for the design of naval structures (Faltinsen, 1990; Abrate, 2013). Planing vessels are continuously subject to

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http://dx.doi.org/10.1016/j.jfluidstructs.2015.08.013
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impulsive loading during sailing and maneuvering, largely affecting their performance and survivability (Gu and Moan, 2002; Faltinsen et al., 2004; Hughes et al., 2013). Despite the geometric complexity of marine vessels, the vast majority of the technical literature has focused on two-dimensional (2D) water entry problems (Abrate, 2013).

By studying 2D water impacts, a number of tractable mathematical models has been developed to predict the hydrodynamic loading experienced by rigid (von Karman, 1929; Wagner, 1932; Korobkin, 2004) and flexible (Faltinsen, 1997; Qin and Batra, 2009; Khabakhpasheva and Korobkin, 2013; Shams and Porfiri, 2015) structures, along with an array of computational techniques to detail the flow physics during the impact (Zhao and Faltinsen, 1993; Battistin and Iafrati, 2004; Stenius et al., 2011). These theoretical studies have been supported by experimental efforts on laboratory-scale models approximating 2D geometries, which have helped isolating the role of the deadrise angle (Chuang, 1966; Tveitnes et al., 2008), heel angle (Shams et al., 2015; Judge et al., 2004), impact velocity (Panciroli and Porfiri, 2013; Tveitnes et al., 2008), geometric curvature (Panciroli et al., 2015; El Malki Alaoui et al., 2012), and structural flexibility (Panciroli and Porfiri, 2015; Stenius et al., 2013).

While these efforts have contributed to an improved understanding of the physics of water impact, the role of 3D phenomena has yet to be fully elucidated. Korobkin and Pukhnachov (1988) have studied the initial stage of the impact of a 3D body on an ideal fluid. Korobkin (2002) has proposed an exact solution for the water entry of an elliptic paraboloid within the framework of Wagner approximation (Wagner, 1932), and additional analytical developments of the framework were presented in Scolan and Korobkin (2001). A further improvement of this solution was proposed in Korobkin (2005), where the modified Logvinovich model (MLM) proposed in Korobkin (2004) was extended to 3D problems to account for nonlinear effects and the geometry of the impacting body. Therein, model predictions for the resultant force were compared with experimental data for an elliptic paraboloid. Scolan (2004) derived a semi-analytical formulation for the hydroelastic impact of a flexible conical shell.

Complementary to these analytical studies, 3D water entry problems have been computationally investigated by Gazzola et al. (2005), Tassin et al. (2012), and Sun and Wu (2013). Specifically, Gazzola et al. (2005) numerically solved a linearized Wagner problem using variational inequalities and validated theoretical predictions against previous findings on a cone (Scolan, 2004) and elliptic paraboloid (Scolan and Korobkin, 2001). Tassin et al. (2012) developed a fast numerical scheme based on Wagner theory and boundary element method. The hydrodynamic force was calculated for three cases of an elliptic paraboloid, a wedge with conical ends, and a square pyramid. Force data were compared with experimental results demonstrating a very close agreement with experimental findings. Oblique water entry of a cone was studied in Sun and Wu (2013), using a boundary element method to solve a potential problem with fully nonlinear boundary conditions imposed on the body and free surface.

Beyond the measurement of the total force during water entry (Tassin et al., 2012), few efforts have sought to evaluate the distributed hydrodynamic loading (Battley and Allen, 2012; Jalalisendi et al., 2015; El Malki Alaoui et al., 2015). Battley and Allen (2012) explored 3D hydrodynamic loading on rigid and deformable wedges entering the water surface at a constant speed, by performing local pressure measurements on select locations on the impacting body. However, 3D effects could not be fully characterized due to the lack of spatially resolved data for the pressure. Using a similar approach, El Malki Alaoui et al. (2015) have recently investigated the impact of a pyramid entering the water surface at a constant velocity. Data from four independent pressure transducers were used to assess the self-similarity of the impact and quantify the role of the entry velocity.

In Jalalisendi et al. (2015), we have proposed an alternative approach for the detailed analysis of 3D water entry without the use of pressure transducers installed on the impacting body. This approach entails the measurement of the flow physics in the vicinity of the body using particle image velocimetry (PIV) (Raffel et al., 2007) and the subsequent reconstruction of the pressure field using Navier–Stokes equations (van Oudheusden, 2013). For a wedge of square base impacting the water in free fall, we have demonstrated that 3D effects have a secondary role on the hydrodynamic loading experienced by the wedge. Specifically, we have found that only the cross-sections proximal to the edges of the specimen are affected by the axial flow along the length of the wedge.

In this work, we seek to extend the analysis to a more complex geometry described by multiple curvatures that result in a highly 3D flow physics. Reconstructing the hydrodynamic loading in the vicinity of a complex shaped model require significant PIV advancements to isolate the flow field in the 3D pile-up region, where the pressure is expected to be maximized (Korobkin, 2004; Tassin et al., 2012). Different from the wedge considered in Jalalisendi et al. (2015), the cross-sections of the model used in this study vary along its axis, causing them to asynchronously impact the water surface.

Our approach is grounded on recent efforts on the use of PIV to study 2D water entry problems (Nila et al., 2013; Panciroli and Porfiri, 2013). Nila et al. (2013) and Panciroli and Porfiri (2013) independently demonstrated the feasibility of indirectly measuring the hydrodynamic loading on a rigid wedge from planar PIV measurements using different computational schemes. Following these initial efforts, additional studies were performed to elucidate the effect of the heel angle on the asymmetric water entry of rigid wedges (Shams et al., 2015); investigate the role of geometric curvature and quantify the energy transfer between the impacting body and the water (Panciroli et al., 2015); analyze the influence of structural flexibility (Panciroli and Porfiri, 2015); and validate the PIV-based pressure reconstruction on synthetic datasets to assess the contribution of several parameters for PIV analysis (Facci et al., 2015).

The main objective of this work is to extend the 3D PIV-based pressure reconstruction technique of Jalalisendi et al. (2015) to study water entry of bodies with a complex geometry, representative of marine vessels (Faltinsen, 2006). The shape of the model is designed to proxy a miniature ship hull. The model enters the water surface with pure vertical