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Experiments on the water entry of curved wedges: High speed imaging and particle image velocimetry

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ABSTRACT

In this work, we experimentally study the water entry of curved rigid wedges. Experiments are performed on two groups of rigid wedges comprising five specimens each. Each group has a fixed mean deadrise angle (25° and 35°) and varying radius of curvature. Drop tests are conducted in free-fall, and the drop height is parametrically varied to investigate the effect of the entry velocity on the pile-up evolution, the impact dynamics, and the energy transferred to the fluid. Specifically, high speed imaging is utilized to simultaneously measure the penetration depth of the wedge and its wetted surface. Experimental results are used to compute the pile-up coefficient, which is found to be largely independent of both the wedge geometry and the entry velocity, while exhibiting modest variations as a function of the penetration depth. In addition, particle image velocimetry is used to investigate the flow physics generated by the water entry, and especially dissect the energy absorbed by the risen water during impact. Results show that between 60 and 80% of the impact energy is consistently transferred to the risen water, which accounts for the formation of the pile-up and the spray jets.

1. Introduction

Over the past few decades, considerable research efforts have been devoted to the development of analytical and numerical tools for the prediction of impact dynamics in water entry problems, due to their scientific and technological relevance in naval engineering (Faltinsen, 1990, 2006; Zhao and Faltinsen, 2006; Korobkin, 1996, 2004; Tassin et al., 2010; Kapsenberg, 2011; Abrate, 2013; Hirdaris et al., 2014). While these approaches have been shown to accurately describe hydrodynamic loading in a multitude of experimental studies, their validation is largely limited to specific geometries, whereby the majority of experimental studies have focused on flat wedges (Bisplinghoff and Doherty, 1952; Greenhow, 1987; Engle, 2003; Wu et al., 2004; Carcaterra and Ciappi, 2004; Tveitnes et al., 2008; Lewis et al., 2010; Stenius et al., 2013), cylinders (Greenhow and Yanbao, 1987; Cointe and Armand, 1987; Garrison, 1996; Battistin and Iafrati, 2003; Sun and Faltinsen, 2006), spheres (De Backer et al., 2009; El Malki Alaoui et al., 2012; Truscott et al., 2012), and cones (De Backer et al., 2009; El Malki Alaoui et al., 2012). More complex geometries, such as paraboloids and pyramids, have only been investigated in theoretical studies (Scolan and Korobkin, 2001; Korobkin, 2002; Gazzola et al., 2005; Korobkin and Scolan, 2006; Moore et al., 2012), and the effect of geometric curvature on the water entry of rigid bodies is yet to be fully experimentally quantified, see also the review by Abrate (2013).

Modeling the impact dynamics often leverages momentum conservation, whereby the fluid is treated as an added mass whose magnitude increases with time during the water entry. One of the seminal studies in this field is attributed to Von Karman (1929), who formulated an approximate scheme to predict the impact dynamics of a flat wedge. Since then, many authors have extended Von Karman's solution to describe water pile-up in the vicinity of the wedge and its effect on the added mass (Wagner, 1932; Chuang, 1996; Payne, 1995; Wu, 1998; Pesce, 2003; Korotkin, 2009). Central to most of these approaches is the pile-up coefficient, which quantifies the ratio between the horizontal projection of the wetted surface of the wedge and its projected surface with respect to the initial water surface. For a flat wedge, Wagner (1932) predicted that such coefficient equals $\pi/2$, independent of the impact dynamics and deadrise angle. In this context, experimental data by Greenhow (1987) offered evidence that the pile-up coefficient of flat wedges does not vary during impact, even if the wedge decelerates as a result of the fluid–structure interaction. However, Wagner's prediction has been shown to often overestimate the pile-up coefficient of flat wedges (Bisplinghoff and Doherty, 1952) and lose accuracy as the deadrise angle increases (Mei et al., 1999). Notably, the implementation of Wagner condition on

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curved bodies indicates that the pile-up coefficient varies during the impact as a function of both the impact dynamics and the geometry (Faltinsen, 2006). However, a systematic experimental analysis of the pile-up coefficient for curved wedges is currently not available.

As an alternative to momentum conservation, a few modeling efforts rest upon the conservation of energy during impact (Scolan and Korobkin, 2003; Cointe et al., 2004). Importantly, as originally demonstrated by Payne (1993) and recently remarked in a comprehensive review by Abrate (2013), theoretical predictions based on energy conservation may differ from those stemming from momentum conservation, due to the energy imparted to the spray jets. Energy-based formulations typically do not account for the energy imparted to the spray jets, resulting in a discrepancy with respect to schemes that are based on momentum balance. As indicated by Payne (1993), such energy may account for half of the kinetic energy of the wedge, with the remaining half being transformed into the kinetic energy of the added mass. Dissecting the energy of the flow region that is generated as the water is pushed sideways by the falling wedge is critical for accurately implementing energy conservation principles. However, a thorough experimental characterization of the energy transferred to the fluid, along with a detailed experimental analysis of its dependence on the geometry of the wedge, is presently lacking.

In this work, we study the water entry of curved bodies to understand the role of the body curvature on the physics of the impact. Toward this aim, we undertake an extended experimental campaign on wedges with varying radius of curvature entering the water in free-fall from several impact heights, for a total of 40 experimental conditions. We consider both positive and negative curvatures to include convex and concave shapes, spanning the typical spectrum of hull geometries that are considered in the design of marine vessels (Okumoto et al., 2009). High speed imaging is utilized to analyze the impact dynamics of the wedges, in terms of their penetration depth, and the water pile-up phenomenon, quantified through the wetted surface. These experimental results are ultimately used to compute the pile-up coefficient, which is found to be largely independent of the curvature and the penetration depth. We utilize the modified Logvinovich model (Korobkin, 2004) to aid in the interpretation of experimental results and offer further validation for such a well-established approach.

In addition, particle image velocimetry (PIV) (Raffel et al., 2007) is leveraged to investigate the unsteady flow physics of the impact. Specifically, PIV data are used to perform a control volume analysis that is aimed at elucidating the energy transfer from the falling wedge to the fluid. In particular, we seek to isolate the energy absorbed by the fluid bulk from the energy transmitted to the risen water, which is responsible for the pile-up phenomenon and the formation of the spray jets. Results demonstrate that variations of the wedge curvature have negligible influence on the portion of the energy imparted to the risen water. In fact, it is found that the energy imparted to the risen water ranges between 60 and 80% of the total energy transferred to the fluid during the water entry, independent of the curvature and the entry velocity.

The rest of the paper is organized as follows. In Section 2, we introduce the experimental drop-weight apparatus used to perform free-fall impacts, along with the data acquisition system. We also formulate the basic framework of a control volume analysis that is performed to evaluate the energy transferred from the falling body to the risen water during the impact. In Section 3, we report experimental results on the effect of the wedge curvature and the entry velocity on the impact dynamics, on the evolution of the water pile-up, and on the energy transferred to the risen water during the impact. Therein, we also compare experimental results on the pile-up coefficient with theoretical findings obtained by implementing Wagner condition, and we compare analytical predictions based on modified Logvinovich model with the experimental findings. Conclusions and final remarks are summarized in Section 4.

2. Experimental setup and data analysis

In this section, we first present the experimental setup for the drop tests, the data acquisition system, and the design of the specimens. Later, we introduce the details of PIV analyses that are performed to evaluate the fluid kinematics. Finally, we detail the control volume analysis used for the evaluation of the energy transferred to the fluid during the water entry.

2.1. Specimens

In this work, two groups of specimens are studied, see Fig. 1. All the samples have the same square base of width and length $L = 200$ mm. Each group has a fixed mean deadrise angle β_0 of 25° or 35° and comprises five specimens with different radii of curvature R. Such radii of curvature are obtained by varying the deadrise angle at the wedge keel β to attain the values $2\beta_0$, $\frac{3}{2}\beta_0$, β_0, $\frac{1}{2}\beta_0$, and 0, according to $R = (L/4)/(\cos\beta_0 \sin(\beta_0 - \beta))$. In the following, we refer to such curvatures with a number from 1 to 5, with 1 identifying the sharpest wedge. Note that curvatures 3 and 5 refer to the special cases of a flat wedge and a cylinder, respectively. Thus, the height is 45 mm and 68 mm for the groups with mean deadrise angle of 25° and 35°, respectively, and the radius of curvature takes the values −131, −255, ∞, 255, and 131 mm (from curvatures 1 to 5, respectively) for the 25° group, and −106, −203, ∞, 203, and 106 mm for the 35° group.

Fig. 2 shows the profiles of the ten specimens, where only half of the geometry is shown due to symmetry. Therein, the y-axis is along the specimen height and x is along the width. With respect to this coordinate, the profile of the cross section of the wedge is

$$y = R\left(\cos\beta - \sqrt{1 - \left(\frac{x}{R} + \sin\beta\right)^2}\right) \tag{1}$$

From now onwards, the color coding in Fig. 2 is used to identify the wedges in all the plots; thus, legends in the following graphs are omitted when possible.

All wedges are composed of an internal ABS skeleton printed in a rapid prototyping machine (Stratasys Dimension SST) covered by a 2 mm thick balsa wood layer. Each skeleton has five ribs uniformly placed along its length; the central rib has a thickness of 20 mm and the others of 4 mm. The balsa wood and the ABS skeleton are glued together with an epoxy adhesive with enhanced resistance to water wearing (Loctite E-30CL). Balsa wood is chosen as external layer for its orthotropic properties that ease the process of fully covering the plastic skeleton, while offering significant stiffness to the wedge during impact. A flowable silicone layer is later applied on the outer surface of the wedges to prevent water absorption and the consequent degradation of the specimens. The total mass of each specimen is approximately 0.2 kg.

2.2. Drop weight apparatus and data acquisition

The drop tests are executed on a custom built drop weight machine for the analysis of water entry problems, see also Panciroli and Porfiri (2013, 2014). The apparatus is comprised of a transparent tank 800 mm long, 320 mm large, and 350 mm deep. The tank is

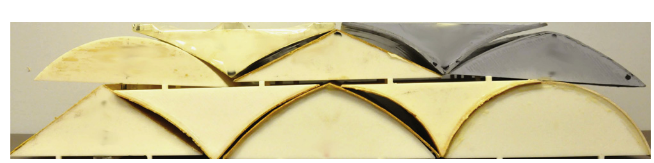

Fig. 1. Curved wedges used in the experimental study; specimens with mean deadrise angle $\beta_0 = 25°$ lie on top of specimens with $\beta_0 = 35°$.