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A numerical study of water entry of asymmetric wedges using a CIP-based model

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ABSTRACT

The two-dimensional water entry of wedges with different inclination angles is numerically investigated using a constrained interpolation profile (CIP)-based model, which is developed on the ground of a fixed Cartesian grid and governed by the Navier-Stokes (N-S) equations. A high-order finite difference method is employed as the flow solver, where the CIP method is used to discretize the convective term. The tangent of hyperbola for interface capturing/slope weighting (THINC/SW) is adopted to capture the free surface/interface, and an immersed boundary method is applied to simulate the motion of bodies. The present numerical model involving symmetric water entry is verified in comparison with the previous numerical and experimental results in the literature. The results of the asymmetric water entry are provided in terms of the penetration depth, velocity, pile-up coefficients, impact force of wedges, and velocity and pressure distributions of fluid. Considerable attention is paid into the effects of deadrise and inclination angles. It is found that the presence of the inclination angle significantly influences both the velocity and pressure field, and further regulates the penetration depth, velocity, pile-up coefficients, and impact force on the wedge. Specifically, wedges entering into the water with small deadrise angles are found to be more sensitive to the inclination angle than those with large deadrise angle.

1. Introduction

The hull slamming generated by the impact of an object on water is of particular interest in ocean engineering, such as ditching of airplane on the sea, water entry of projectiles, ship slamming, and so on. When a vessel sails in rough seas or a spacecraft lands on the water surface, such motion always causes an asymmetric impact. The quasi-V-shaped cross-sections are commonly used near the bottom of vessels, for the sake of simplicity, it is convenient to use a wedge to investigate the asymmetric impact problems. It is well known that the presence of an inclination angle can lead to fully different hydrodynamic behaviours between the asymmetric and symmetric entries. Thus the present work will focus on the influence of inclination angle in hydrodynamics.

The water entry problems falls into two main difficulties: (i) the duration of impact (order of milliseconds); (ii) the very complicated flow phenomenon such as jet flow, splashing, flow separation, air cushion, and cavitation. This phenomenon has received considerable attention in the past decades (Seddon and Moatamedi (2006); Abrate (2011); Truscott et al. (2014)). Based on the conservation of momentum, Von Karman (1929) firstly introduced added mass concept and predicted the impact pressure to study the water entry problem of two-dimensional wedge. The fluid was assumed to be inviscid and irrotational, the surface tension, gravity, the piled-up water on the wedge and structural elasticity effects were neglected. His results underestimated the impact force when the deadrise angle of wedge was small. Then Wagner (1932) extended Von Karman (1929)'s method to predict the pressure distribution on a two-dimensional wedge during water entry. The piled-up water on the wedge has been taken into account by simply introducing a constant surface wetting factor. As a result, the impact force for wedges with small deadrise angle was overestimated. The jet flow and flow separation were still neglected in the study. Most of following analytical models for asymmetric water entry derived from Wagner's theory and overcame its drawbacks. Garabedian (1953) initiated the study of oblique entry problem based on Wagner's theory, subsequently Korobkin (1988) studied the inclined entry of a blunt profile into an ideal fluid at the initial stage. Toyama (1993) extended Wagner's theory, by considering the piled up water at the free surface near the wedge which is associated with the pressure distribution and the peak value, to predict the slamming pressure distribution on the surface of asymmetric wedges. However, the flow separation was omitted. Vorus (1996) extended Tulin (1957)'s slender surface model to flat-cylinder theory. Following this theory, Xu et al. (1998) studied the asymmetric impact problems. The jet

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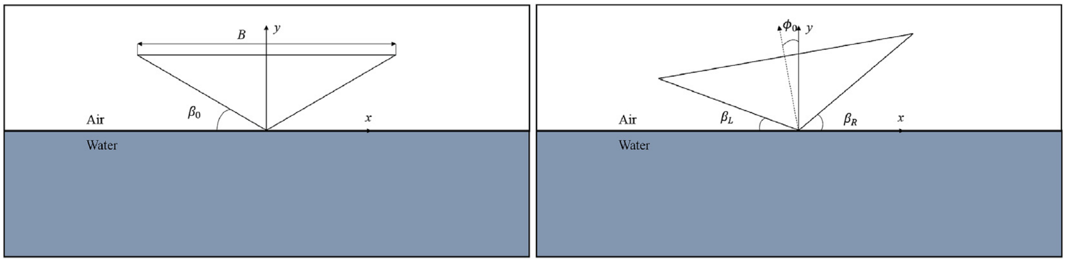

(a) Symmetry (b) Asymmetry

Fig. 1. Configuration of the wedge at the onset of the impact.

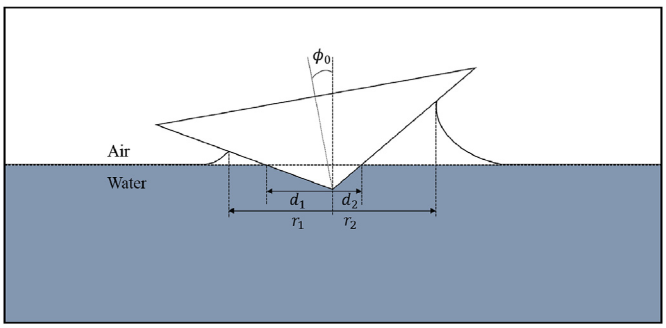

Fig. 2. Configuration of the wedge during the impact.

formation and initially separated flow due to large asymmetry were investigated. They classified the asymmetric impact flow model into two types and demonstrated the role of the inclination angle on the acceleration of a wedge impacting the still water asymmetrically. Semenov and Iafrati (2006) presented a nonlinear analytical self-similar solution to the asymmetric water entry flow of a wedge with vertical velocity. The flow in the jet was considered as well. The free surface elevation, contact angles at the intersection with the wedge boundary, pressure distribution, force and moment coefficients were examined. Due to the water entry of a wedge is not generally self-similar (especially for the free fall of asymmetric wedges), the boundary element method on the frame of potential flow theory has also been used for the water entry problem. Xu et al. (2008) adopted Wu et al. (2004)'s boundary element method to analyze the free surface elevation, pressure distribution over the wedge surface, and impact force under the considerations of different deadrise angles and oblique entry with constant velocity. In addition, the analytical solutions based on the shallow water approximation was used to model the jet flow.

All theoretical studies provide valuable insight to asymmetric water entry, however, which are limited to understand the complicated phenomena during water entry. The application of refined flow measurements offers a good way to thoroughly study the physics of impact. Compared to symmetric entry, the asymmetry of flow field brings more challenges, thus the experiments on the asymmetric cases are quite rare. Xu et al. (1999) conducted a series of experiments to validate Xu et al. (1998)'s method for predicting impact force and moment. A wedge with different heel angles and weights was freely dropped from different heights. The resulting motions of test models at asymmetric impact include vertical water entry and transverse rolling. Judge et al. (2004) experimentally studied a wedge of 37° deadrise angle with a heel angle of 0° to 34° and an oblique entry velocity. Initial separation-ventilation of the flow near the wedge keel due to asymmetric impact or horizontal-vertical impact velocity was observed in their works. Shams et al. (2015) considered a wedge of 37° deadrise angle with a heel angle of 0° to 35°, which impacts the quiescent fluid vertically from a fixed

Table 1
Different mesh sizes used in the CIP calculations, lengths in (m).

Type of impact	Case No.	min Δx	min Δy
Symmetric	Mesh 3	0.005	0.005
	Mesh 2	0.002	0.002
	Mesh 1	0.001	0.001

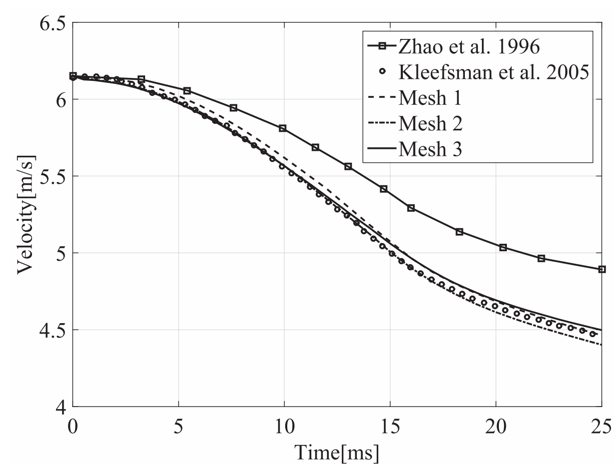

Fig. 4. Vertical velocity of symmetric impact.

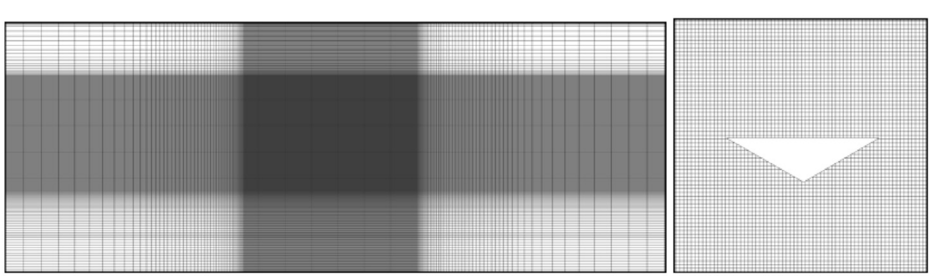

Fig. 3. The computational mesh of water entry.