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# Simulation of water entry of a two-dimension finite wedge with flow detachment

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ABSTRACT

A two-dimensional finite wedge entering water obliquely at a prescribed speed is considered through the velocity potential theory for the incompressible liquid. The gravity is also included. The problem is solved by using the boundary element method in the time domain. The method of the stretched coordinate system is adopted at the initial stage. A condition is imposed at the intersection of the free surface and the body surface after flow detachment to allow the liquid to leave the body surface smoothly. A new methodology is developed to treat free jet with free surface on both sides. The auxiliary function method is used to calculate the pressure on the body surface. Detailed results for the free surface shape and pressure distribution are provided, and the effect of physical parameters on water entry is discussed.



## 1. Introduction

Fluid/structure impact of a solid body entering the water surface is a common problem in naval architecture, ocean engineering, coastal engineering and many other areas. In the mathematical modelling and numerical simulation, the water entry of a two-dimensional wedge is a typical example. Based on the assumption of inviscid and incompressible liquid, Dobrovol'skaya (1969) obtained a self-similar solution for a wedge in vertical entry with constant speed, using the conformal mapping in which the complex velocity potential satisfied the nonlinear free surface boundary condition. Zhao and Faltinsen (1993) considered the same problem using the boundary element method in the time domain. The thin jet was cut near its tip. Wu et al. (2004) solved the problem through using the Cauchy theorem for the complex potential and the jet was approximated using the shallow water equation. This was extended by Xu et al. (2008) for the problem of oblique entry of an asymmetric wedge. Adopting the integral hodograph method and using the velocity magnitude and direction as the variables, Semenov and Iafrati (2006) solved the problem of vertical water entry of an asymmetric wedge. The above work is principally for a wedge of infinite length, in which the flow will never depart from the wedge. In practice, a wedge has finite height. The flow will depart from the body when it has passed the knuckle. We notice that the word 'flow separation' is commonly used in turbulent flow. The reality is that in such a case the liquid is still attached to the body surface or there is in fact no flow detachment. In the present case, the liquid does detach from the body surface. Thus, we have chosen to use 'flow detachment' to describe the flow passing the knuckle. In such a case, the flow characters and solution procedure will be very much different. One noticeable example is that the flow for the wedge will no longer be self-similar even at constant

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speed and zero gravity.

Zhao et al. (1996) considered the problem of water entry beyond the stage that the flow has passed the knuckle of the wedge. The velocity continuity condition was imposed at the detachment point. Gravity effect was ignored and the jet was cut. Experimental studies were undertaken at the same time. This model was extended to planing vessels by Sun and Faltinsen (2007). Iafrati and Battistin (2003) investigated a symmetrical wedge vertically entering the calm water at constant speed while Wang et al. (2015) experimentally and numerically studied this problem in freefall. Tassin et al. (2014) used an analytical model based on the Logvinovich model for water entry of a finite wedge with flow detachment. Sun and Faltinsen (2009) simulated a finite bow-flare section with roll angle vertically entering the calm water and compared their result with the experimental data (Aarsnes, 1996). While the above work is based on the potential flow, Oger et al. (2006) used the smooth particles hydrodynamics (SPH) method to simulate water entry of an asymmetric wedge while Gu et al. (2014) used the by level set method. In experiments, the photos in Greenhow and Lin (1983) and Tveitnes et al. (2008) also show some very interesting features of the flow after the free surface has detached from the body.

A thin and long jet is usually developed during water entry. Pressure in the jet region is almost equal to the atmospheric one, and it usually does not significantly contribute to the impact load on the body. As a result, cutting the thin jet was often applied in the simulation of water entry (Zhao and Faltinsen, 1993, Battistin and Iafrati, 2003, Sun and Faltinsen, 2007). However, based on authors' own experience, such a technique could cause some local numerical error near the new jet tip. Also this may not affect the force on the body in the attached flow, cutting the jet at early stage may significantly affect the free surface shape after flow detachment. Iafrati and Battistin (2003) kept the jet flow in their numerical simulation, while their work was for a symmetric problem without gravity effect. Linear approximation was applied in the jet flow. In this paper, a new method is proposed for the free jet. As the pressure on the both sides of the jet is atmospheric, it can be shown through the momentum equation that the jet in such a case is in fact in free fall motion. This allows the velocity and movement of the jet to be obtained directly and independently without involving any numerical solution. The results can then be used in the boundary integration equation for the velocity potential. This can be maintained until the integrals over the both sides virtually cancel each other. In such a case, the jet can be taken out form the integral equation, which is physically equivalent to cutting the jet.

The present paper considers the water entry of a finite wedge at a prescribed velocity. The water entry will be asymmetric if the wedge has a heel angle or both vertical and horizontal velocity. The gravity is also included, which was shown by Sun et al. (2015) becoming more important as time increases. When flow departs from the body, it is assumed that the particle will leave the body tangentially. Thus the slopes of the free surface and the body surface will be the same at the knuckle. The normal velocity will then be continuous at the point. Detailed results for the free surface shape and pressure distribution are given and their physical meaning is discussed.

## 2. Mathematical model and numerical procedure

### 2.1. Governing equation and boundary conditions

A two-dimensional finite wedge entering water obliquely at a prescribed speed is considered here, which has left deadrise angle $\gamma_1$ and right deadrise angle $\gamma_2$ as shown in Fig. 1. We define a Cartesian coordinate system $O$-$xy$ fixed in space, in which the $x$-axis is along the undisturbed water surface and the $y$-axis is vertically upwards. At $t=0$, the tip of the wedge is at the origin of the coordinate system. The translational velocity of the wedge is $\boldsymbol{U}=U\boldsymbol{i}-V\boldsymbol{j}$, where $\boldsymbol{i}$ and $\boldsymbol{j}$ are the unit vectors in the $x$ and $y$ directions respectively. Here the minus sign before $V$ means that it is positive when the body moves downwards. The wedge has finite height with breadth $B$ at the top and its half inner angle, or the angle between its symmetry line (dashed line in the figure) and its face is $\gamma$. Heel angle $\theta$ is the angle between the symmetry line and the $y$ axis. These angles form the following relationships:

$$\gamma_1 = \frac{\pi}{2} + \theta - \gamma, \gamma_2 = \frac{\pi}{2} - \theta - \gamma \tag{1}$$

The fluid is assumed to be incompressible and inviscid, and the flow irrotational. A velocity potential $\Phi$ can then be introduced, which satisfies Laplace equation

$$\nabla^2\phi = 0 \tag{2}$$

in the fluid domain. On the body surface $S_0$, we have from the impermeable condition

$$\frac{\partial\phi}{\partial n} = \boldsymbol{U}\cdot\boldsymbol{n} = U\cdot n_x - V\cdot n_y \tag{3}$$

where $\boldsymbol{n}=(n_x,n_y)$ is the normal vector of the body surface pointing out of the fluid domain. The Lagrangian form of the kinematic and dynamic conditions on the free surface $S_F$ can be written as

$$\frac{Dx}{Dt} = \frac{\partial\phi}{\partial x}, \frac{Dy}{Dt} = \frac{\partial\phi}{\partial y} \tag{4}$$