Applied Ocean Research 65 (2017) 262–278

Contents lists available at ScienceDirect

Applied Ocean Research

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

Simulation of freefall water entry of a finite wedge with flow detachment

C.M. Bao [a], G.X. Wu [a,b,*], G. Xu [c]

[a] College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, PR China
[b] Department of Mechanical Engineering, University College London, London WC1E 7JE, UK
[c] School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, PR China

A R T I C L E I N F O

Article history:
Received 22 November 2016
Received in revised form 17 March 2017
Accepted 28 April 2017

Keywords:
Oblique water entry
Boundary element method
Flow detachment with free jet
Free fall motion
Multi degrees of freedom
Auxiliary function

A B S T R A C T

A two-dimensional finite wedge entering water obliquely in freefall with three degrees of freedom is considered through the velocity potential theory for the incompressible liquid. The problem is solved by using the boundary element method in the time domain. The scheme of the stretched coordinate system is adopted at the initial stages when only a small part of the wedge near its tip has entered water. The auxiliary function method is adopted to decouple the nonlinear mutual dependence between the body motions in three degrees of freedom and the fluid flow. When the liquid has detached from the knuckle of the wedge, the free jet is treated through the momentum equation. The developed method is verified through existing results for one degree of freedom in vertical motion. Various case studies are undertaken for a wedge entering water vertically, obliquely and with rotational angles. Results are provided the accelerations, velocities, pressure distribution and free surface deformation, and the physical implications are discussed.

1. Introduction

Fluid/structure impact is a major concern for marine and coastal structures. A typical example is slamming of a ship. At large heave and pitch motion, its bow can emerge from water and then reenter water at high speed. When that happens, the ship may also have sway and roll motions. In such a case, each cross section of the ship enters water obliquely together with rotational velocity. A two dimensional wedge is commonly used in analysis. One reason is that the cross section of high speed craft is V-shaped. Another important reason is that understanding obtained from a wedge is highly relevant to many more general cases.

There has been extensive research on problems related to fluid/wedge impact, based on the incompressible velocity potential theory on the basis that the Mach number in such a case is relatively small and the period of impact is very short. Based on whether water entry is in freefall or in the prescribed motion, and whether the wedge is finite or infinite in width, the work can be broadly divided into four categories. In the first category, an infinite wedge enters water with prescribed velocity, either constant or varying. In the first category, an infinite wedge enters water with prescribed velocity, either constant or varying. Dobrovol'skaya [1] used the complex conformal mapping to consider a symmetric wedge vertically entry water with constant speed. She obtained a self-similar solution which satisfied the nonlinear free surface boundary condition. Zhao & Faltinsen [2] considered the same problem using the boundary element method in the time domain. Adopting the integral hodograph method and using the velocity magnitude and direction as the variables, Semenov & Iafrati [3] solved the problem of vertical water entry of an asymmetric wedge. Using the Cauchy theorem for the complex potential, Xu et al. [4] solved the problem of oblique entry of an asymmetric wedge.

In the second category, the wedge is finite in width. However the entry speed is still prescribed as either constant or varying. In such a case, the flow will detach from the knuckle of the wedge shortly after initial impact. The flow after detachment is no longer self similar even at constant speed and zero gravity. Zhao et al. [5] considered vertical water entry of a symmetric wedge. The velocity continuity condition was imposed at the knuckle after flow detachment. They also carried an experiment to verify their numerical results. Iafrati & Battistin [6] investigated a symmetrical wedge vertically entering the calm water at constant speed. Tassin et al. [7] used an analytical model based on the Logvinovich model for a finite wedge. Bao et al. [8] simulated oblique water entry for an asymmetrical wedge. The gravity effect was included. The fluid was assumed to leave the knuckle tangentially after flow detachment. The thin jet flow was treated through momentum equation from which the

* Corresponding author at: College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, PR China.
E-mail address: g.wu@ucl.ac.uk (G.X. Wu).

http://dx.doi.org/10.1016/j.apor.2017.04.014
0141-1187/

solution could be obtained independently and directly. Semenov & Wu [9] obtained the self-similar solution of an expanding wedge. When the ratio of the expansion speed to the entry speed is below a limit, flow detachment can occur.

In the third category, an infinite wedge enters water in free fall motion. Before the body touches water, its acceleration is equal to that due to gravity. As the body enters water, the acceleration changes due to hydrodynamic force. It becomes unknown and has to be found from the solution of the problem. The body motion and the fluid flow is therefore fully coupled. Wu et al. [10] considered a symmetric wedge vertically entering water in free fall motion. The nonlinear mutual dependence of the body motion and fluid flow was decoupled by the auxiliary function method [11]. Experiment was also undertaken and the acceleration from the simulation was in good agreement with the measured data at initial stage. While the wedge in the above work has only one degree of freedom, or the body is allowed to move only vertically downwards, Xu et al. [12] considered water entry of a wedge through free fall in three degrees of freedom. When rotation is included, the flow is no longer self similar even when the speed is constant as the ratio of the translational velocity and the angular velocity can be a length scale. Stability and accuracy of the numerical simulation is more important in three degrees of freedom, as numerical error could lead to motion instability.

In the fourth category, the wedge entering water through free fall motion is finite in width. Sun [13] simulated a wedge entering water vertically. The results were compared with the experimental data of Aarsnes [14]. More recently, Wang et al. [15] further studied this problem numerically and experimentally. However, it is still limited to one degree of freedom. The present work considers a finite wedge entering water through free fall motion in three degrees of freedom. Before flow detachment, the problem is similar to that considered by Xu et al. [12] for an infinite wedge. However, gravity effect in the free surface boundary condition and on the hydrodynamic force will be included here. Major differences occur after flow detachment. For an infinite wedge, its wetted surface keeps increasing and most part will be eventually above the rotational center located at the center of gravity. The rotational moment will change its sign during water entry, which may stop the body to rotate continuously in one direction, as it does during ship capsize. For a finite wedge the wetted surface will be constant after flow detachment. The moment may remain in the same direction and the body may continue to rotate in the same direction. Furthermore, after flow detachment, free jets may be formed [8]. Its accuracy should be ensured as the body motion can be very much affected by numerical error.

In the following sections, we shall first give the mathematical formulation and numerical procedure. Brief discussions will then be given about the boundary element method for solving the velocity potential and about the auxiliary function method to decouple the mutual dependence between the body motion and fluid flow. Before providing numerical results, convergence study is undertaken and comparison is made with available numerical and experimental data. Extensive case studies are then provided to show the behaviour of the body motion in three degrees of freedom, as well as the corresponding pressure distribution and free surface deformation.

2. Mathematical model and numerical procedure

2.1. Governing equation and boundary conditions

The two-dimensional oblique water entry problem of finite width with breadth $\tilde{B}$ at the top through free fall motion is considered here. The water density $\tilde{\rho}$, the vertical velocity $\tilde{V}$ at the moment

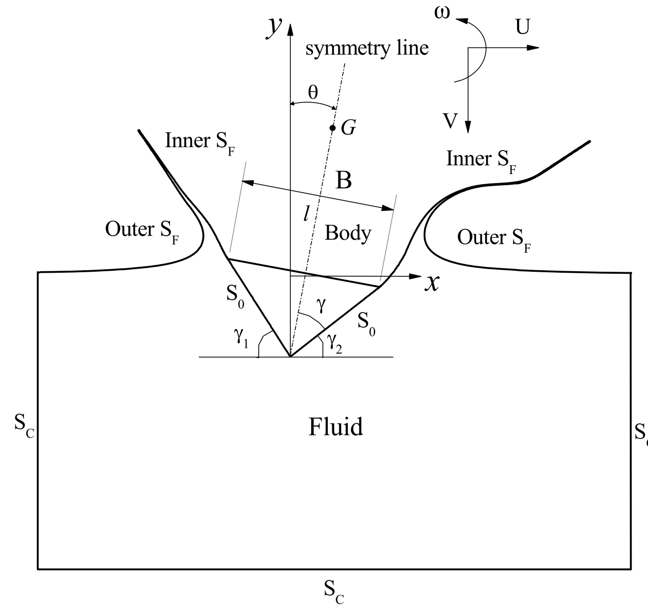

Fig. 1. Sketch of the problem.

of entry and the breadth $\tilde{B}$ are used for the nondimensionalisation. Subsequently, the parameters without ~ are nondimensional. The problem is sketched in Fig. 1. A Cartesian coordinate system O–xy fixed in the space is defined, in which x-axis is along the undisturbed water surface and y-axis is vertically upwards. Heel angle θ in the figure is the angle between the symmetry line of the wedge and the y-axis. The wedge is asymmetric and has left and right deadrise angles γ_1 and γ_2, respectively, and the angle between its symmetry line and its face is γ. These angles form the following relationships:

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

At $t = 0$, the tip of the wedge is touching the calm free surface. We set the origin of the system at the point. The rotating center is located at the center of the gravity G. The distance between G and the tip of the wedge is l. The translational velocity of the wedge at point G is $\boldsymbol{U} = U\boldsymbol{i} - V\boldsymbol{j}$, and the rotational velocity about G is $\boldsymbol{\Omega} = \omega\boldsymbol{k}$, where $\boldsymbol{i}$ and $\boldsymbol{j}$ are the unit vectors in the x and y directions respectively, and $\boldsymbol{k} = \boldsymbol{i} \times \boldsymbol{j}$. Here the minus sign before V means that it is positive when the body moves downwards. We notice that $V = 1$ at $t = 0$ based on the way in which the parameters are defined.

The fluid is assumed to be incompressible and inviscid, and the flow to be irrotational. A velocity potential ϕ 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

$$\frac{\partial\phi}{\partial n} = (\boldsymbol{U} + \boldsymbol{\Omega} \times \boldsymbol{X}) \cdot \boldsymbol{n} = (U - \omega Y)n_x + (-V + \omega X)n_y \tag{3}$$

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

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

$$\frac{D\phi}{Dt} = -\frac{y}{Fr^2} + \frac{1}{2}|\nabla\phi|^2 \tag{5}$$