Applied Ocean Research 50 (2015) 30–46

Contents lists available at ScienceDirect

Applied Ocean Research

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

Constant acceleration exit of two-dimensional free-surface-piercing bodies

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ARTICLE INFO

Article history:
Received 4 April 2014
Received in revised form 28 June 2014
Accepted 14 July 2014
Available online 13 January 2015

Keywords:
Water exit
Nonlinear free surface
Complex potential
Conformal mapping
Added-mass force
IBVP

ABSTRACT

The forced constant acceleration exit of two-dimensional bodies through a free-surface is computed for various 2D bodies (symmetric wedges, asymmetric wedges, truncated wedges and boxes). The calculations are based on the fully non-linear time-stepping complex-variable method of Vinje and Brevig (1981). The model was formulated as an initial boundary-value problem (IBVP) with boundary conditions specified on the boundaries (dynamic and kinematic free-surface boundary conditions) and initial conditions at time zero (initial velocity and position of the body and free-surface particles). The formulated problem was solved by means of a boundary-element method using collocation points on the boundary of the domain and stepped forward in time using Runge–Kutta and Hamming predictor–corrector methods. Numerical results for the deformed free-surface profile, pressure along the wetted region of the bodies and force experienced by the bodies are given for the exit. The analytical added-mass force is presented for the exit of symmetric wedges and boxes with constant acceleration using conformal mappings. To verify the numerical results, the added-mass force and the numerical force are compared and give good agreement for the exit of a symmetric wedge at a time zero ($t = 0$) as expected but only moderate agreement for the box.

1. Introduction

The study of water entry has a wide range of applications in ocean engineering, especially in extreme or survival situations such as ship slamming or the ditching of aircraft. For such situations it is vital to know the pressure distribution on the submerged part of the body and the force acting on it. Because of the nature of the free-surface conditions, the flow is, in general, difficult to calculate. However, for the above applications, at least in the early stages of entry, the flow can be realistically treated as potential and only in the vertical plane so that the problem is two-dimensional. Moreover, for high-speed entry gravity is usually ignored. In his seminal paper Wagner [16] also assumed that the deadrise angle was small, allowing the matching of an inner flow around an expanding flat plate to be matched to a planing-plate flow representing the spray jet. For a modern treatment see [7]. Another approach for wedges moving with constant speed (more generally with displacement being some power of time t) is to exploit self-similarity, see [5,17].

In this paper we focus our attention on the study of water exit of surface-piercing bodies. Although this problem is usually less violent than that of entry, it has received far less attention in the literature. Perhaps part of the reason here is that none of the above approximations are valid. The initial draft of the body introduces a length scale which precludes self-similarity; equally gravity is essential to the filling of the hole that would otherwise be left by the exiting body. These two constraints imply that the problem is essentially Froude-number dependent and this makes analytical progress virtually impossible. This does not explain the dearth of published experimental results though; perhaps the exit problem is considered less important in engineering applications. Such a view is not valid for ship slamming, where velocity of entry of the ship's bow is determined by the previous motion during the exit phase. Another application is in marine crane operations where one needs to keep control of a body being lowered through the free surface in wave conditions to avoid snatching of the cables. This involves exit as well as entry relative to the moving wave surface. State-of-the-art engineering practice is reviewed in DNV [4].

We exploit the complex potential method of Longuet-Higgins and Cokelet [9] for extreme waves and further developed by Vinje and Brevig [14,15] for floating or submerged bodies. Greenhow [6] used this method to study the exit of submerged cylinders and presented initial results for wedge exit. We here present interesting results for the exit of symmetric wedges, asymmetric wedges, truncated wedges and a box body. The acceleration of the exiting body is constant and comparable to gravity, meaning that the effect of gravity on the loads will be significant. Certainly

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http://dx.doi.org/10.1016/j.apor.2014.07.007

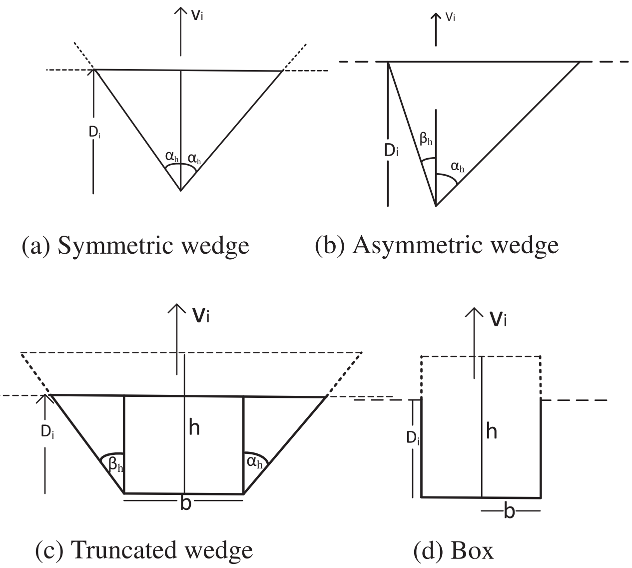

Fig. 1. Geometrical representation of the different shaped bodies for water exit cases.

some of these bodies are likely to shed strong vortices from their corners, but these are ignored in this study. We hope that the present results will act as benchmarks and stimulate further theoretical and experimental work to assess the effects of vortices.

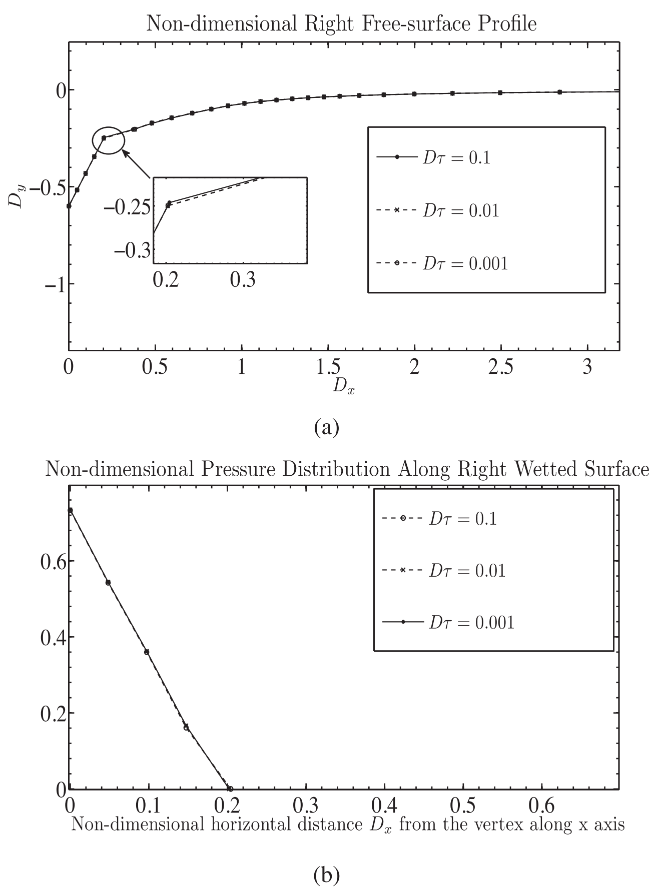

Fig. 2. Convergence of the symmetric wedge SW30 submerged at a non-dimensional initial depth $\widehat{D_i} = -1$ exiting with constant acceleration of $G_\tau = 0.8$ and plotted at a non-dimensional time $\tau = 1$. $\alpha_h = 30^\circ$.

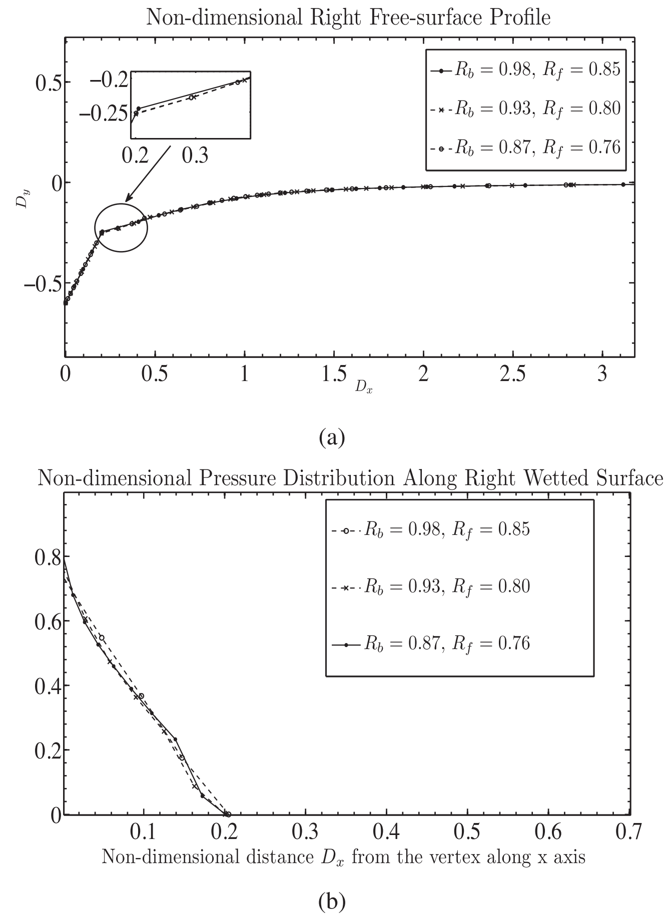

Fig. 3. Convergence of the symmetric wedge SW30 submerged at a non-dimensional initial depth $\widehat{D_i} = -1$ exiting with constant acceleration of $G_\tau = 0.8$ and plotted at a non-dimensional time $\tau = 1$. $\alpha_h = 30^\circ$. R_b and R_f are ratio of the body points and the free-surface point spacings, respectively; NBODY = 50 and NF = 70 are the number of points on the body surface and the free surface, respectively.

2. Mathematical methods

We can describe the motion of the system of fluid particles and the moving body in a two-dimensional complex Cartesian coordinate system. The particles on the body surface and the free surface can be considered by a mixed Eulerian and Lagrangian description, respectively. We assume the fluid is incompressible and the flow around the body irrotational so that the potential flow theory is applicable. The mathematical formulation and the solution of Vinje and Brevig's numerical technique are explained in the Appendices A and B for the convenience of the reader (especially given the age and relative obscurity of their publications).

The method is a boundary-integral method based on Cauchy's theorem, where the contour C comprises the free surface, the body surface, the bottom and distant vertical boundaries (see Fig. A.16). We let a collocation point z_k move onto the boundary from outside C giving

$$\pi\psi(z_k) + Re\left\{\int_{C_0} \frac{\phi + i\psi}{z - z_k} dz\right\} = 0, \quad \forall z_k \in C^{\phi}, \tag{1}$$

or

$$\pi\phi(z_k) + Re\left\{i\int_{C_0} \frac{\phi + i\psi}{z - z_k} dz\right\} = 0, \quad \forall z_k \in C^{\psi}, \tag{2}$$

where C^{ϕ} is the part of C where the velocity potential ϕ is known, C^{ψ} that where the stream function ψ is known and C_0 is C minus a