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Oblique impact of a water cone on a solid wall

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ABSTRACT

The hydrodynamic problem of oblique impact of a water cone on a solid wall is investigated by the three dimensional (3D) velocity potential flow theory. The time stepping method is used in a stretched coordinate system to track the moving water surface where the fully nonlinear dynamic and kinematic boundary conditions are satisfied through an improved Eulerian method. In particular the free surface elevation and potential variation are updated at a given azimuth in each θ plane of the cylindrical coordinate system, to overcome the numerical difficulties caused by the complex variation of the 3D curved free surface. Remeshing and smoothing are applied regularly along the intersection lines of the free surface and each θ plane. Detailed convergence study with respect to a time step and element size has been undertaken and high accuracy has been achieved. Extensive simulations are made for perpendicular and oblique impacts. Detailed results for pressure and free surface profile are provided.

1. Introduction

The high speed impact by violent ocean waves on structures has a wide range of applications in coastal, ocean engineering and naval architecture. Extremely large fluid loading can be created during the process. In some cases, consequences can be catastrophic, causing loss of lives and destroying structures. Impact usually occurs within a very short period of time, over which both the fluid velocity and fluid pressure change rapidly with time and with location. This is accompanied by large and rapid deformation of the liquid surface. All these pose great challenges in fluid mechanics.

Although dynamically similar, the fluid/structure impact problem can be broadly divided into two kinds. One is a moving structure hitting a stationary liquid and the other is a moving liquid hitting a stationary structure. A typical example of the former is water entry, or a solid body falling through the water surface. Early work based on the simulation includes that by Shiffman and Spencer [1] on a cone which was also considered by Mackie [2] using the linearised boundary condition. The 2D self-similar problem of a wedge with fully nonlinear free surface boundary conditions was solved by Dobrovol'skaya [3] based on the complex potential. Zhao and Faltinsen [4–6] used the boundary element method and solved the water entry problem through the time stepping method. Lu et al. [7] included the elastic deformation of the wedge in the coupled hydrodynamic/structural problem. Semenov and Iafrati [8] considered an asymmetric wedge in vertical entry. Oger and Doring [9] and Shao [10] used the SPH method to simulate the water entry of a wedge. Lin [11] used the viscous flow theory for a cylinder. Wu et al. [12] adopted a boundary element method together with a shallow water approximation for the jet along the body surface and solved the problem of water entry of a wedge in free fall motion in a stretched coordinate system, together with an auxiliary function to decouple the mutual dependence of the hydrodynamic force and the body acceleration. Xu et al. [13] solved the problem of an asymmetric wedge in oblique entry with constant speed. They then considered an asymmetric wedge entering water through free fall motion in three degrees of freedom [14] and a cone in free fall motion [15]. Wu [16] demonstrated that a self-similar solution would be possible even at varying entry speed. He then developed a higher order boundary element method to solve the problem. While the above work is either two dimensional or axisymmetric, Sun and Wu [17,18] focused on the three dimensional problems of a cone entering water obliquely at constant speed and a non-axisymmetric body at varying speed, respectively.

The second kind of fluid/structure impact problem, that of moving fluid hitting the structure, is more closely related to wave impact on the solid wall considered in this paper. Cumberbatch [19] obtained the mathematical solution for vertical impact of a symmetrical liquid wedge on a horizontal flat surface. A numerical solution for a similar problem was obtained by Zhang et al. [20]. Cooker and Peregrine [21] simulated a water-wave impact on a vertical wall with the gravity effect. Hattori et al. [22] undertook experimental study on the wave impact on a wall including the effect of the trapped air. Greco [23] studied the impact of green water on deck. Shu [24] considered the oblique impact of a breaking wave

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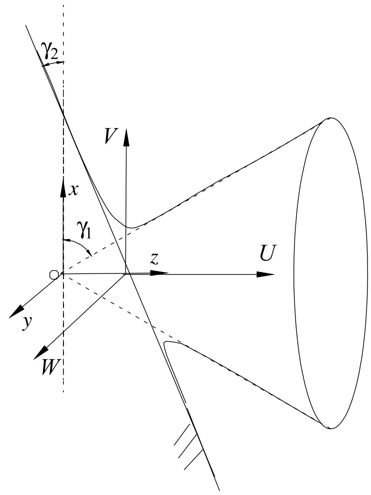

Fig. 1. Sketch of the problem.

on a wall. Wu [25] used the complex velocity potential with the boundary element method and obtained the similarity solution for head-on collision between symmetrical solid and liquid wedges. Christodoulides and Dias [26] solved the steady flow problem of a rising stream hitting a plate of finite extent. For axisymmetric cases, Xu et al. [27] solved the problem of a liquid block of finite size hitting on a solid surface.

Here, we shall consider the oblique impact of a cone-shaped incoming water column hitting a solid wall. When the axis of the water cone is not perpendicular to the solid surface, the problem is no longer axisymmetric and has to be solved by the fully 3D method. This presents much bigger challenge than the 2D or axisymmetric case. The water cone will deform significantly after the impact, and tracking the rapidly moving 3D curved free surface in time domain becomes one of the major difficulties. We shall use an improved Eulerian method to update its position and the potential on the free surface. Results for the pressure distribution on the solid surface and non-axisymmetric free surface deformation caused by the oblique impact are presented and discussed in detail, aiming to shed some insights into this important problem.

2. Mathematical model and numerical procedure

We consider the problem of the oblique impact of a water cone on a solid wall. In the physical model, the wall is stationary and the water moves at a high speed towards the surface. Mathematically it is more convenient to use the dynamically equivalent model, in which the solid plane moves with the same speed towards the stationary water cone, as shown in Fig. 1. A right-handed Cartesian coordinate system O–xyz fixed in space is defined, in which the positive z axis coincides with the axis of the cone, and the origin is at the tip of the undisturbed water cone. The angle between the water cone surface and O–xy plane is denoted by γ_1. The wall is assumed to have a flat surface and to be inclined, which is obtained by rotating the O–xz plane about the y axis by an angle γ_2. When $\gamma_2 = 0$, the problem becomes axisymmetric. The velocity components U, V and W in Fig. 1 are the constant velocity components of the rigid surface in z, x and y directions respectively. Physically when the surface of the wall is flat, the fluid flow will be influenced only by the normal velocity of the surface and will be independent to its tangential velocity component. This means that when the total projection of U, V and W in the normal direction is the same, the fluid flow will be the same and will not depend on individual U, V and W. Thus without losing generality, we need to consider only the case with $V = W = 0$.

The impact of interest usually has high speed and the period of impact is very short. Thus the viscosity effect is neglected as it takes time to develop [28]. The fluid compressibility is also ignored. As a result, the fluid flow can be described in terms of the velocity potential ϕ which satisfies Laplace's equation. In the dynamic condition on the free surface, the surface tension and gravity are also ignored:

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0. \tag{1}$$

The initial surface of the water cone can be written as

$$x^2 + y^2 = z^2 \tan^2(\pi/2 - \gamma_1) \tag{2}$$

and the surface of the moving wall at time t as

$$z = -x \tan\gamma_2 + Ut. \tag{3}$$

The boundary condition on the flat wall surface can be written as

$$\frac{\partial\phi}{\partial n} = U\cos\gamma_2 \tag{4}$$

in which $\mathbf{n}$ is the normal of the body surface pointing into the fluid domain. On the free surface

$$z = \zeta(x, y, t) \tag{5}$$

both the dynamic and kinematic boundary conditions need to be satisfied. Their Eulerian form can be respectively written as

$$\phi_t + \frac{1}{2}(\phi_x^2 + \phi_y^2 + \phi_z^2) = 0 \tag{6}$$

$$\zeta_t = \phi_z - \zeta_x\phi_x - \zeta_y\phi_y. \tag{7}$$

Far away from the wall, the fluid is assumed to be undisturbed. Thus we have

$$\phi \to 0 \qquad \sqrt{x^2 + y^2 + z^2} \to \infty. \tag{8}$$

2.1. Tracking of the free surface

It is convenient to define a cylindrical coordinate system O–θrz with

$$x = r\cos\theta, \qquad y = r\sin\theta \tag{9}$$

and the dynamic and kinematic boundary conditions of the free surface (6) and (7) become

$$\phi_t + \frac{1}{2}(\phi_r^2 + (\phi_\theta/r)^2 + \phi_z^2) = 0 \tag{10}$$

$$\zeta_t(r, \theta, t) = \phi_z - \zeta_r\phi_r - \frac{\zeta_\theta\phi_\theta}{r^2}. \tag{11}$$

As the disturbed fluid domain changes dramatically with time, it is convenient to define the potential in a stretched coordinate system [12]

$$\phi(r, z, \theta, t) = sU\varphi(\alpha, \beta, \theta, t), \quad \alpha = r/s,\ \beta = z/s \tag{12}$$

in which $s = Ut$. With this definition, the surface of the initial water cone satisfies

$$\alpha = \beta\tan(\pi/2 - \gamma_1) \tag{13}$$

and the surface of the rigid wall satisfies

$$\beta + \alpha\cos\theta\tan\gamma_2 - 1 = 0. \tag{14}$$

The normal of the rigid surface can be written as

$$n_\alpha = \cos\theta\sin\gamma_2, \qquad n_\beta = \cos\gamma_2, \qquad n_\theta = -\sin\theta\sin\gamma_2. \tag{15}$$