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Oblique water entry of a wedge into waves with gravity effect

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ABSTRACT

The hydrodynamic problem of a two dimensional wedge entering waves with gravity effect is analysed based on the incompressible velocity potential theory. The problem is solved through the boundary element method in the time domain. The stretched coordinate system in the spatial domain, which is based on the ratio of the Cartesian system in the physic space to the vertical distance the wedge has travelled into the water, is adopted based on the consideration that the decay of the effect of the impact away from the body is proportional to this ratio. The solution is sought for the total potential which includes both the incident and disturbed potentials, and decays towards the incident potential away from the body. A separate treatment at initial stage is used, in which the solution for the disturbed potential is sought to avoid the very large incident potential amplified by dividing the small travelled vertical distance of the wedge. The auxiliary function method is used to calculate the pressure on the body surface. Detailed results through the free surface elevation and the pressure distribution are provided to show the effect of the gravity and the wave, and their physical implications are discussed.

1. Introduction

Fluid/structure through water entry of a body into a wave is an extremely important problem in naval architecture and ocean engineering. A particular example is during a ship advancing in rough seas. It is common that very large motion of the ship can be excited by the hostile waves. The bow of the ship can emerge from the water and then re-enters into the wave with high speed. This causes severe fluid/structure impact, or slamming. During the process, very large pressure can be generated. In some extreme cases, a ship can be damaged as a result. Another example is a large wave hitting an offshore platform at high speed. This is dynamically equivalent to a structure entering a wave.

The water entry problem is usually based on the incompressible velocity potential theory through the consideration of the impact time and the Mach number. Work in this area can be broadly divided into two categories. The first one is based on the Wagner theory together with some asymptotic analysis. It starts with the solution for the body below the calm water, in which the velocity potential is assumed to be zero on the undisturbed flat free surface. From the solution the wave elevation is obtained, which will intersect with the body surface and therefore the wetted surface of the body will be altered. The potential obtained for the body below the calm water should then be modified. This means there will be some implicit coupling between the potential and the wetted body surface. The typical work based on the Wagner theory includes those by Howison et al. (1991) for bodies with small deadrise angles, Faltinsen (2002) on a wedge with finite deadrise angle

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and by Korobkin et al. (2006) for a body with elastic deformation. Korobkin also used the second order Wagner theory for wave impact (Korobkin, 2007). The second category for this problem is based on the fully nonlinear theory in which the nonlinear boundary conditions are imposed on the instantaneous positions of the body surface and the free surface. Among the typical work, Dobrovol'skaya (1969) and Zhao and Faltinsen (1993) considered vertical entry of a wedge. Semenov and Iafrati (2006) solved the problem of vertical entry of an asymmetric wedge, while Xu et al. (2008) investigated the case of oblique entry of an asymmetric wedge. The problem of twin wedges was solved by Wu (2006). While all these are based on the constant entry speed. Wu et al. (2004) considered vertical entry of a wedge in free fall motion with a single degree of freedom, and Xu et al. (2010) considered the free fall with three degrees of freedom, in which the vertical motion is coupled with the horizontal and rotational motion.

All these above studies are, however, for body entering into calm water without the gravity effect. Faltinsen (1990) considered a linear incident wave. The velocity potential generated by the body during water entry is assumed to be equal to zero on the incoming wave surface. For the gravity effect, Sun and Faltinsen (2007) used the fully nonlinear theory for a wedge entering water in the context of planning vessels advancing in calm water. The present paper considers water entry of a wedge into waves with gravity effect based on the stretched coordinate system (Wu et al., 2004). The presence of the incoming wave has led to some major challenges in solution. First the problem is no longer self-similar even when the wedge has constant speed and the problem has to be solved in the time domain. Secondly, in the stretched coordinate system, the small wetted surface of the wedge at the initial stage can be amplified by the distance that the wedge has travelled in the vertical direction. The size of the computational domain can remain more or less the same. However when the potential in the physical system, which is the incident wave potential when the body touches the wave, is amplified by the travelled distance of the wedge, the potential in the stretched system will become very large. Thirdly, far away from the body the potential in the stretched system does not tend to zero but the incident potential. All these require the computational methodology to be refined.

Water entry of a wedge into waves with gravity effect has led to some new physical features. The velocity distribution of the fluid flow due to the incident wave alters the relative velocity between the body and the liquid. This means even when the body entry speed is the same at each point, local relative speed at each point of the body surface may be not be the same. Furthermore, even during the vertical entry, the horizontal velocity of the fluid due to the wave means that the body equivalently impacts the water obliquely. This changes significantly the free surface shape near the body and pressure distribution on the body. The slope of the wave also alters the deadrise angle during the impact, which is one of the major factors affecting the jet development and pressure distribution. The gravity effect may be negligible at initial stage. Its importance will become more and more important as the impact continues. All these will be shown through the detailed numerical results provided in the paper.

The analysis in this paper is based on the incompressible velocity potential flow theory. The boundary element method (BEM) is used at each time step to solve the boundary value problem with governing Laplace equation. The experience in the previous publications with wave has shown such a model can give many global results accurately. However, without the proper Kutta condition at the tip of the wedge, the solution in this local area is expected to be non-physical. Also the model does not include the air cavity which could be trapped on the body surface during water entry. This further limits its applications.

2. Mathematical model and numerical procedure

2.1. Governing equation and boundary conditions

The 2-D problem considered here is given in Fig. 1 which shows a wedge entering a wave obliquely at a constant speed. A Cartesian coordinate system $O-x_0y_0$ fixed in the space is defined so that the x_0-axis coincides with the mean water surface and z_0-axis points upwards and passes though the tip of the body when it touches the water. The wedge, with deadrise angles γ_1 and γ_2 on right and left hand sides respectively, has a downwards vertical velocity W and a horizontal velocity U along the x_0 direction. When the fluid is assumed to be incompressible and inviscid, and the flow to be irrotational, the velocity potential ϕ whose gradient is equal to the fluid velocity can be introduced. The vertical velocity of the wedge W, the acceleration due to gravity g, and the water density ρ are used for dimensionalisation. Thus the length scale, the time t, the velocity, the velocity potential ϕ, the dynamic pressure P, the force F, the wave number and the wave circular frequency are measured based on W^2/g, W/g, W, W^3/g, ρW^2, $\rho W^6/g^2$, g/W^2, g/W respectively. The potential ϕ satisfies the Laplace equation in the fluid domain

$$\frac{\partial^2\phi}{\partial x_0^2}+\frac{\partial^2\phi}{\partial y_0^2}=0. \tag{1}$$

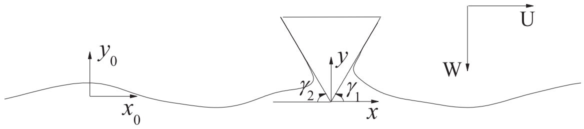

Fig. 1. Sketch of the problem.