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Water impact of horizontal circular cylinders and cylindrical shells

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Abstract

A two-dimensional boundary element method (BEM) is developed to simulate the water flow during the water impact of a horizontal circular cylinder. Exact free surface conditions are satisfied. The non-viscous flow separation on the curved surface of the cylindrical can be simulated by merging a local analytical solution with the numerical method. The BEM is first applied to solve the water impact of a rigid horizontal circular cylinder. The calculated results are compared with experiments. Good agreement is obtained. The BEM is also applied to solve the water impact problem of an elastic cylindrical shell, while a modal analysis is utilized for structural responses and the hydroelasticity, i.e. water–structure interaction is considered. Flat plate theories are used initially instead of the BEM to avoid the numerical difficulties in the initial stage. The calculated structural responses are compared with the experimental results and reasonable agreement can be achieved.

Keywords: Water impact; Hydroelasticity; Cylindrical shell; Fluid–structure interaction; Boundary element method; Non-viscous flow separation

1. Introduction

The slamming on horizontal cylindrical members of a jacket in the free surface zone is of concern in offshore operations. Due to the relative motion between the waves and the jacket, the members can go into and out of the water. The slamming loads on the horizontal members can cause damage on the structures and was a motivation for the experimental and theoretical studies by Faltinsen et al. [1]. The hydroelastic impact loads and the resulting stresses on a horizontal circular cylinder were examined by using a generalized von Karman method for the hydrodynamic loads and a beam model for the cylinder. Another application in marine technology is the bottom slamming on the bulbous bow of a ship, in which the bulb can be viewed as a part of a circular cylinder.

When horizontal cylinders impact with the water waves, an equivalent process is a rapid water entry of horizontal cylinders into initially calm water. Neglecting the variation along the length of the cylinder, one can study a two-dimensional problem in the cross plane. If the cylinders are solid or the impact velocity is small, they can be regarded as rigid bodies. However, if they are flexible in the cross plane with thin walls and the impact velocity is large, a cylindrical shell model should be used and hydroelasticity must be considered.

Even for a rigid circular cylinder, it is not easy to exactly solve the water impact problem, because the free surface will initially change very rapidly and the process may involve many complicated effects, such as due to air cavity, flow separation, breaking waves. Actually, the rate of change of the wetted surface is initially infinite according to Wagner [2]. Approximate methods, i.e. flat plate theories [3], are often used in practice. To exactly solve the problem with fully nonlinear free surface conditions, numerical methods have to be used. Greenhow [4] studied the water entry of a rigid circular cylinder by using a boundary element method based on Cauchy's theorem. However, the calculations need to be refined and the flow separation model needs to be improved to be more stable. Zhu et al. [5] used a CIP method to study the water entry of a rigid circular cylinder. The time history of the body motion and the evolution of the free surface contours are well predicted except at the initial time due to the infinite rate of change of the wetted surface. The method accounts for viscous effects and air–water interaction. However, it is time consuming as all computational fluid dynamics (CFD) methods are and is hard to be applied to practical problems. In this paper, a boundary element method is developed to solve the same water entry problem. The non-viscous flow separation is simulated

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by merging an analytical solution of a separated flow with the BEM. The thin jet along the body surface and the thin spray evolved from the separated flow are cut away in the numerical simulations. The numerical method is convergent and stable.

For a cylindrical shell impacting on the free surface, it is necessary to consider the hydroelasticity when the cylinder's wall is thin and flexible and the impact velocity is large. Shibue et al. [6] experimentally studied the water impact of a cylindrical shell. Arai and Miyauchi [7] investigated the water impact of cylindrical shells, both experimentally and numerically. A CFD method was applied for the flow field and a modal analysis was used for the shell structure. Bereznitski [8] also studied Arai and Miyauchi's experiments [7] by means of commercial software (Dytran). A flat plate theory was used by Ionina and Korobkin [9] to solve the water impact of a cylindrical shell. All these investigations contribute in some aspects. Nevertheless, there are still many unsolved problems, for example, the possibility of ventilation, air cavity and cavitation and the importance of the initial impact force. In the present study, all these issues mentioned above as well as other effects related to the structural model and experimental error sources will be discussed through the calculations by the BEM together with a modal analysis for the structural response. Further, a BEM-based calculation is expected to be faster than a CFD method and more accurate than an approximate method by flat-plate theories. Therefore, the BEM is more promising from a practical point of view.

From the study of the blunt bottom impact problem by Korobkin [10], water compressibility matters in an initial supersonic stage. However, in the present problems, the duration of the supersonic stage is extremely short. So the acoustic effects are excluded in the present study.

In this paper, the numerical solver is first applied for the water impact of rigid cylinders. The predicted body motions and the free surface elevations agree well with the experiments. Then the BEM is combined with a modal analysis to solve the water impact of cylindrical shells, with the BEM for the water flow and the modal analysis for the structural responses. The free drop tests by Arai and Miyauchi [7] are numerically studied. Time series of strain response are calculated. Reasonably good agreement between the calculations and the experiments can be obtained. Many factors can affect the calculated results. They are analysed one by one. The analyses of these factors not only provide physical insights into the water impact process, but also give valuable information on how to perform the numerical simulations more efficiently.

2. Theories

2.1. Description of the water field

As shown in Fig. 1, a circular cylinder or a cylindrical shell is penetrating the water surface with a time varying vertical water entry speed $V(t)$. A space-fixed Cartesian coordinate system yoz is used, with the y-axis on the initially calm free surface, and the z-axis going through the centre of gravity of

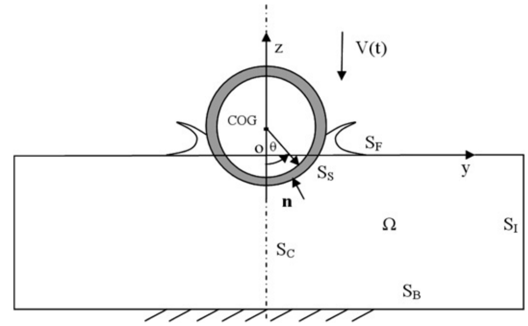

Fig. 1. Coordinate system and definitions.

the body and pointing upwards. Due to the symmetry about the z-axis, only one half of the fluid domain for $y > 0$ is studied. This half fluid domain in two dimensions denoted as Ω is surrounded by a boundary S consisting of a body surface S_S, a free surface S_F, a vertical far-field boundary S_I, a bottom S_B and a symmetry boundary S_C. The fluid is assumed inviscid and incompressible with an irrotational flow. Therefore a velocity potential $\varphi(y, z, t)$ satisfying the 2D Laplace equation $\partial^2\varphi/\partial y^2 + \partial^2\varphi/\partial z^2 = 0$ in the fluid domain Ω can be used to describe the fluid flow. Surface tension is neglected and the kinematic and dynamic boundary conditions on the free surface are

$$\frac{Dy}{Dt} = \frac{\partial\varphi}{\partial y}, \qquad \frac{Dz}{Dt} = \frac{\partial\varphi}{\partial z},$$
$$\frac{D\varphi}{Dt} = \frac{1}{2}|\nabla\varphi|^2 - gz \quad \text{on } S_F. \tag{1}$$

Here D/Dt means the substantial derivative and g is the acceleration of gravity. The dynamic free surface condition implies that the pressure on the free surface is constant. A consequence is that the air flow between the cylinder bottom and the free surface before the water impact is neglected. Further, a closed air cavity may be created above the cylinder at a late stage of the cylinder penetration. This effect depends on the Froude number with V as a characteristic velocity [5] and would necessitate that the compressibility of the air cavity should be accounted for. However, this effect is not present in our studies, but in principle it is feasible to account for the effect. The boundary condition on the body surface S_S is

$$\frac{\partial\varphi}{\partial n} = \mathbf{V}\cdot\mathbf{n} + \dot{w} \quad \text{on } S_S \tag{2}$$

where $\mathbf{V} = -V(t)\mathbf{k}$ is the velocity of the rigid motion of the cylinder, $\mathbf{k}$ is the unit vector along the positive z-axis, $\mathbf{n}$ is the normal vector on the body surface pointing into the body. When the cylinder is an elastic shell, the body surface S_S is the undeformed mean shell surface and the term $\dot{w} = \partial w/\partial t$ is the normal vibration velocity with positive direction pointing to the centre. For a rigid body, $\dot{w}$ is zero. For an elastic shell, the body boundary condition in Eq. (2) is originally satisfied on the instantaneous deflected shell surface. If we assume that the displacement is much smaller than the radius of the cylinder, we can Taylor expand the boundary condition around the mean position of the shell surface and neglect the high