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Wave radiation and diffraction by a floating rectangular structure with an opening at its bottom in oblique seas *

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Abstract: The radiation and the diffraction of linear waves by a rectangular structure with an opening at its bottom floating in oblique seas of finite depth are investigated. Analytical expressions for the radiated potentials and the diffracted potential are obtained by use of the method of separation of variables and the eigenfunction expansion method, with the unknown coefficients being determined by the boundary conditions and the matching requirement on the interface. The hydrodynamic coefficients and the wave excitation forces are verified using the symmetry properties of coupled hydrodynamic coefficients and one specific example investigated previously. By use of the present analytical-numerical solution, the influences of the angle of incidence, the width of the opening on the wave forces and the hydrodynamic coefficients are investigated. It is also found that in the oblique sea the external excitation frequency that can lead to the resonance of a rectangular tank depends on the wave direction and the wave number of the incident wave.

Key words: Oblique-wave radiation and diffraction, floating structure with an opening, analytical-numerical solution, hydrodynamic coefficient, wave excitation force

Introduction

The wave interaction with floating structures has attracted many investigations of hydrodynamics during the past few decades due to its importance in the ocean engineering, the design of marine structures, and other fields, with extensive publications on the hydrodynamics of floating structures and significant achievements. To evaluate the hydrodynamic coefficients and the wave forces of the floating structures, various numerical and analytical methods are used with consideration of the interaction between the normal or oblique incident waves and the intact structures[1-6]. As a semi-analytical solution procedure, the method of separation of variables is commonly used. The method is principally used for rectangular and circular bodies. In the former case, the studies include the wave radiation due to oscillations of horizontal rectangular structures[7], the wave radiation and diffraction by an infinitely long rectangular structure floating on the free surface[8], the motion of a floating structure that restricts in some way the motion of a portion of the free surface[9], the two-dimensional piston-like steady-state motions of a fluid in a moonpool formed by two rectangular hulls[10], the motion of a damaged ship in waves based on a theoretical and experimental study[11], the radiation and diffraction problem of a two-dimensional rectangular body with an opening at its bottom floating on a layer of water of finite depth based on the linearized velocity potential theory and an analytical-numerical solution procedure[12], the wave radiation by an infinitely long rectangular structure floating on the free surface in oblique seas[13], the radiation and the diffraction of linear water waves by an infinitely long rectangular structure submerged in oblique seas of finite depth[2], the effects of a bottom sill on the hydrodynamic coefficients, the wave force, and the reflection and transmission coefficients of a rectangular structure floating on the free surface[14], and the diffraction of

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obliquely incident waves by a floating structure near a wall with a step-type bottom topography[15].

The method of separation of variables is also widely used for floating semicircular and circular cylinders. The studies include the complete solution of a floating semicircular cylinder in infinite water depth using the multiple expansion method[16], the second order wave diffraction and radiation as well the second order wave reflection and transmission by a horizontal cylinder in finite water depth[17].

In addition, there are some other methods for the wave interaction with floating structures, such as the radiation and the diffraction of a ship with a forward speed studied by using a time domain Rankine panel method[18] and the wavy (oscillatory both in space and in time) properties of free-surface flows due to presence of floating bodies analyzed within the framework of the potential-flow theory in the development of the multi-domain method[19].

In this paper, we consider the linear wave radiation and diffraction by a rectangular structure with an opening at its bottom floating on the free surface in oblique seas. This kind of structures can be seen in moonpools and damaged ships. Firstly, unlike the studies of the interaction between the normal incident waves and the structures, the governing equation for the radiated potentials and the diffracted potential is not the two-dimensional Laplace equation but the two-dimensional modified Helmholtz equation. The wave excitation forces can be calculated from the incident and diffracted potentials. The focus is the effect of the incident angle on the hydrodynamic forces. Secondly, unlike the studies of the interaction between oblique waves and intact structures, we consider a rectangular tank with an opening at its bottom. Due to the existence of the opening, the external water will flow into a confined domain, which leads to a complex internal motion. In particular, a confined domain usually has a number or even an infinite number of natural frequencies. When the frequency of the incident wave or the motion of the structure is close to one of these frequencies, very large or violent liquid motions may be caused in the confined domain.

To the best of the authors' knowledge, there are no analytical-numerical results reported for the radiation and the diffraction by a floating rectangular structure with an opening at its bottom in oblique seas. For this purpose, the wave diffraction and the wave radiations, including heave, sway and roll by a rectangular structure with an opening at its bottom floating in oblique seas are calculated by an analytical-numerical method. The whole fluid domain is divided into several subdomains. The velocity potential in each subdomain is derived by using the method of separation of variables. The unknown coefficients are determined by the boundary conditions and the matching requirement on the interface of each subdomain. The results are verified through a convergence study, the symmetry property of the hydrodynamic coefficients and one specific example investigated previously. In addition, the effects of the angle of incidence, the width of the opening on the wave forces and hydrodynamic coefficients are discussed in detail.

1. Governing equation and boundary conditions

An infinitely long rectangular structure of width $2b$ and draught h_1 is floating on the water of constant water depth h. The structure has a hole of width $2a$ in the middle of its bottom. A Cartesian coordinate system $oxyz$ shown in Fig.1 is employed with the origin at the undisturbed water surface. The z coordinate points upwards and the x axis is directed to the right. Here it is assumed that the structure is infinitely long in the y direction and the incident wave direction forms an angle $\theta(0^{\circ} < \theta < 90^{\circ})$ with the x-axis. The structure is vertically placed through the hull, the inside water is connected to the outside water with a cavity and a free liquid surface. Its upper part is not closed.

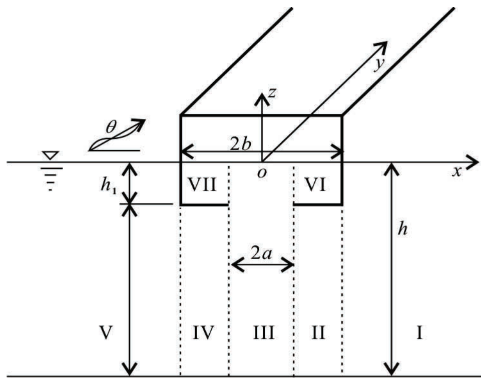

Fig.1 Sketch of geometric configuration

We assume that the fluid is inviscid, incompressible, and that the motion is irrotational, and so the fluid flow can be described by the velocity potential theory. It is assumed that the incoming wave is small, the motions of the structure are small, and the oscillations of the structure vary sinusoidaly in the y direction. The linear theory can be used (These assumptions were adopted by many researchers, as reviewed by Zheng et al.[13]). When the incoming wave is periodic both in the space and in time, the total velocity Φ can be expressed as

$$\Phi(x,y,z,t)=\mathrm{Re}[\eta^{(0)}(\phi^{(0)}+\phi^{(4)})\mathrm{e}^{\mathrm{i}ky\sin\theta}\mathrm{e}^{-\mathrm{i}\omega t}]+$$

$$\mathrm{Re}\left[\sum_{l=1}^{3}-\mathrm{i}\omega\eta^{(l)}\phi^{(l)}(x,z)\mathrm{e}^{\mathrm{i}ky\sin\theta}\mathrm{e}^{-\mathrm{i}\omega t}\right] \quad (1)$$