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A direct coupling numerical method for solving three-dimensional interaction problems of wave and floating structures

Jeng-Hong Kao [a,*], Jaw-Fang Lee [a], Yu-Chun Cheng [b]

[a] Department of Hydraulics and Ocean Engineering, National Cheng Kung University, Tainan, Taiwan, ROC
[b] Fifth River Management Office, Water Resources Agency, Chiayi, Taiwan, ROC

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ABSTRACT

In this article, a direct numerical method is developed to solve three-dimensional interaction problems of wave and floating structures. In the problem formulation, the diffracted wave and radiated wave by the structure are represented as one induced wave potential. The wave field is simulated using a boundary element method, and the structure motions are of six degrees of freedom. In the solution procedure, the structural motions are expressed in terms of wave potentials, which are then substituted into the wave model. The created linear algebraic system is then calculated. The present numerical model is used to simulate a floating rectangular cuboid deployed in a wave channel, and the results are compared with a theory to confirm the accuracy. The present numerical model is further used to calculate a floating structure deployed in an open sea to show the capability of the three-dimensional computation.

1. Introduction

Floating breakwaters are considered as alternatives to conventional fixed breakwaters deployed in coastal areas for preserving small marinas and recreational harbors from attacks of wave forces. The main advantages of floating breakwaters are (a) low-cost construction independent of water depth and seabed geological conditions, (b) easy transportation, especially for temporary facilities, and (c) ecologically advantageous since the water circulation, biological exchange, and sediment transport beneath the structure are allowed. Thus, many studies have been undertaken to investigate the performance of various types of floating breakwaters.

Regarding problems of wave interaction with free floating structures, Ijima et al. [1] presented an analytic solution for wave interaction with a rectangular floating structure in two dimension, in which free floating and spring moored structures were considered. Au and Brebbia [2] used a boundary element method calculating wave forces acting on two-dimensional structures, where submerged, floating and arbitrary geometrical structures were considered. Huang [3] used a finite element method for solving interference problems between water waves and two-dimensional or three-dimensional ocean structures. The added mass, damping coefficient and wave force were discussed for different wave periods. Matsui et al. [4] solved water wave diffraction and radiation by arbitrarily shaped three-dimensional bodies using a hybrid integral equation method. The boundary element idealization was used only in an inner fluid region close to the body and local depth irregularities, while an analytical solution was employed in the outer region of constant depth extending to infinity. The two representations were matched on a fictitious vertical cylindrical surface. Lee [5] presented an analytic solution to solve the heave radiation problem of a rectangular structure. The nonhomogeneous boundary value problem was linearly decomposed into homogeneous ones, which can be readily solved. Yilmaz [6] solved the diffraction and radiation problems of a group of truncated vertical cylinders using an exact analytical method. Abul-Azm and Gesraha [7] studied wave–structure interaction problems. The structure has three degrees of freedom in motion. The research results discussed elimination effects of wave and structure motions in different configurations. Chen et al. [8] presented a complete analytic solution for wave interacting with two-dimensional floating structures by applying the analytic approach for nonhomogeneous boundary value problems proposed by Lee [5]. Diamantoulaki et al. [9] aimed at assessing the effect of pontoon spacing on the performance of floating free or moored twin pontoon breakwaters using a panel method. The results showed the

* Corresponding author. Tel.: +886 6 2757575x63200; fax: +886 6 2741463.
E-mail address: m93520009@mail.ntou.edu.tw (J.-H. Kao).

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roll response decreased while pontoon spacing increased for both free and moored pontoon floating breakwaters. Kim et al. [10] investigated the characteristics of bending moments, shear forces and stresses at unit connections of very large floating structures (VLFS) under wave loads. The characteristics of bending moments, shear forces and stresses at unit connections were discussed at numerical examples. The three-dimensional diffraction of obliquely incident water waves by a floating structure near a wall with step-type bottom was studied using a small amplitude wave theory [11]. The wave forces and the wave elevations on the free surface were investigated for different incident wave angles and water depth ratios.

For wave interaction with tension-leg or spring mooring floating structures, Lee and Lee [12] developed an analytical solution for the coupled linear problem. The fluid-induced drag on the tension legs was not considered. The only force from tension legs was the pre-tensioned force, which provided part of the stiffness of the floating structures. Lee [13] solved tension-leg structures interacting with linear waves. The eigen-function representations of the velocity potential and surface elevations of scattering and radiation waves were developed by Lee and Lee [12]. Analytical solutions showed that the inertia drag on tension legs was negligible compared to that due to the evanescent waves caused by the wave–structure interaction. Lee et al. [14] presented an analytical solution for the dynamic behavior of both the platform and tethers in the tension leg platform system. Elchahal et al. [15] studied wave interaction with a moored floating breakwater with a harbor boundary, and the effects of various structural parameters of the breakwater on the transmitted wave heights were discussed. Ker and Lee [16] proposed an analytical solution for the problem of waves incident on a porous tension leg platform (TLP). The permeable floating body was considered as anisotropic and homogeneous. Results showed that the drags in the porous body change the TLP behavior significantly. Lee and Ker [17] further presented an analytic solution for problems of two-dimensional tension leg structures, where the floating structure was composed of impermeable and porous regions.

Floating structures with attached mooring lines can also be found in the literature. Sannasiraj et al. [18] considered moored floating structure subjected to incident waves, where the stiffness of the mooring lines was calculated using the catenary cable equation. Structural motions and mooring forces for three different mooring configurations were discussed. Diamantoulaki and Angelides [19] considered the performance of an array of floating breakwaters connected with hinge joints under the action of linear monochromatic waves in the frequency domain. The effects of the configuration of hinge joints on the response and effectiveness of the freely floating array were investigated. To date, in the solutions to interaction problems of wave and floating structures, the wave field was decomposed into a scattering problem and radiation problem. The scattering and radiation problems were solved independently; then the solutions were combined together with equations of motion of the floating structures to solve the entire problem.

In this study, the direct coupling method can obtain wave fields by solving one liner algebraic system. The wave fields induced by the floating structure including scattering and radiation waves are considered as a whole induced wave potential. With a given incident wave, the induced wave potential together with motions of the floating structure is solved, where the wave problem is calculated using a boundary element method. The advantage of the proposed method is reduced computer computational time and shorter time to obtain the calculation results. The effect is more significant for the three-dimensional problem.

2. Description and solution for the three-dimensional problem

The problem considered is a floating rectangular cuboid subjected to oblique incident waves, as shown in Fig. 1. A Cartesian coordinate system is adopted with positive x directed to the right, positive y into the paper, and positive z axis upward. The water depth is h, length and width of the structure are $2l$ and $2b$, respectively, and draft is d. Incident waves propagate in the positive x direction, and the surface elevation is η^I. The center of rotation of the structure is located at $C(x_c, y_c, z_c)$ and the gravity center is $O(x_o, y_0, z_o)$. With the action of incident waves, in addition to induced waves around the floating structure, the floating structure is in six-degree of freedom motion.

For steady periodic problems, the potential function of incident waves can be expressed as

$$\Phi^I(x,y,z,t) = \phi^I(x,y,z)e^{-i\omega t} \quad (1)$$

where

$$\phi^I(x,y,z) = iA^I \frac{g}{\omega} \frac{\cosh K(z+h)}{\cosh Kh} e^{iK(x \cos \alpha + y \sin \alpha)} \quad (2)$$

in which A^I is wave amplitude, K is wave number ($K = 2\pi/L$), L is wave length, α is incident angle, ω is angular frequency ($\omega = 2\pi/T$), t is wave period, g is gravity constant and $i = \sqrt{-1}$.

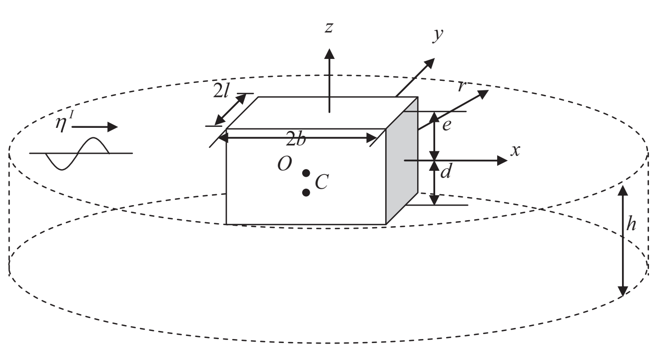

Fig. 1. Definition sketch of 3D waves interacting with a floating structure.