Engineering Analysis with Boundary Elements 69 (2016) 119–131

Contents lists available at ScienceDirect

Engineering Analysis with Boundary Elements

journal homepage: www.elsevier.com/locate/enganabound

Interactions of fully nonlinear solitary wave with a freely floating vertical cylinder

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ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
3 March 2016
Accepted 16 May 2016
Available online 25 May 2016

Keywords:
Solitary wave
Transient wave-structure interaction
Fully nonlinear theory
Higher-order boundary element method

ABSTRACT

Fully nonlinear numerical interaction of a transient wave with a three dimensional structure has been analysed based on a higher-order boundary element method (BEM). The BEM mesh on the free surface is generated through a combination of the structured and unstructured meshes. Through some auxiliary functions, the mutual dependence of fluid/structure motions is decoupled, which allows the body acceleration to be obtained without the knowledge of the pressure distribution. The solitary wave is used as the case study for the transient wave. It is obtained by the third order theory and the fully nonlinear theory. The accuracy of the present numerical model is verified through the steady propagation of a solitary wave and comparison with the published results for solitary wave interaction with a vertical wall. Simulations are then made to study solitary wave interaction with a truncated cylinder. Numerical results are provided for motions, forces and run-ups on the cylinder and comparison between results for the fixed cylinder and the freely floating cylinder is also made.

1. Introduction

For an offshore platform installed in the sea, it will encounter a variety of ocean waves. A good understanding of the mechanism of wave interaction with a structure is of vital importance for the safety of the personnel and the platform, the protection of the environment and investment. When the wave is small, which means that its amplitude is small relative to its length and the typical dimension of the structure, the problem can be linearized in the simulation. In such a case, linear superposition can be used. An incoming wave can be decomposed into a various components. When the interactions of the structure with some typical wave components have been established, their combinations can then be used for a variety of waves. However, in large waves which in fact pose the major threat to the operation of the platform, the linear theory is no longer valid and superposition is no longer applicable. In such a case, each wave has to be considered separately.

There has been extensive work on a structure in nonlinear periodic waves, in particular the Stokes waves. Typical work includes Ferrant [1,2], Ferrant et al. [3], Ducrozet et al. [4], Zhou et al. [5] and Zhou and Wu [6], where the total wave elevation and the total velocity potential are separated into two parts, based on the incoming wave from infinity and the disturbed potential by the body. The other type of work on the nonlinear problems in simulation is to follow the practice in the experiment in a physical tank. Wave is generated on one side while an artificial beach is installed on the other side. Typical work includes those by Ma et al. [7], Wu and Hu [8], Wang and Wu [9] and Ma and Yan [10] using the finite element method (FEM), and those by Liu et al. [11], Bai and Eatock Taylor [12], Bai et al. [13], Yan and Liu [14] based on the boundary element method (BEM).

The research on the nonlinear periodic waves has greatly improved our understanding of their interactions with a platform. A particular example is that the natural frequencies of tension-leg platform (TLP) and gravity-based platform (GBS) constructed from vertical cylinders are well above the dominant frequency of the wave. Although TLP and GBS with this kind of design avoid the linear resonance, resonance may be excited by higher order nonlinear force [6]. This can have serious implication to springing which usually refers to the resonant response of a platform in the stochastic sea state, when the stochastic properties of the motion have become steady. It is highly relevant to the fatigue analysis of the structure. A platform with such a design may also experience ringing, which is a transient response dominated by high frequency components. Ringing is more likely to be excited by a transient wave with a large peak or few peaks. It can last for a while even when the wave has well passed the structure [15–17].

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http://dx.doi.org/10.1016/j.enganabound.2016.05.004
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The present work aims to shed some lights on how a nonlinear transient wave will interact with a floating structure. We choose the interaction between the solitary wave and a freely floating vertical cylinder as the example. The work can be readily extended to other types of transient waves and some realistic offshore structures [6]. There has been extensive research on propagation of the solitary wave, based on KdV equations with first order theory [18], second-order theory [19] and third order theory [20], as well as the fully nonlinear theory [21,22]. There has also been extensive work on the reflection of a solitary wave by a vertical wall, which can be seen as a special case of solidary wave interaction with a structure. Most of them are carried out in the two dimensional. Maxworthy [23] and Chen and Yeh [24] conducted experiments on it. Cooker et al. [25], Craig et al. [26] and Chambarel et al. [27] used BEM to solve the fully nonlinear equations, where the incoming wave is given by the fully nonlinear theory [21]. Su and Mirie [28] carried out a perturbation analysis of two colliding solitary wave to the third order of accuracy. For the case of a fixed body, Sun et al. [29] used the first order solitary wave as the incident wave and studied its behaviour when passing a horizontal rectangular cylinder through the fully nonlinear simulation based on the FEM in two dimensional domains. For the three dimensional problems, Yates and Wang [30] reported an experimental study on solitary waves scattered by a vertical cylinder. Mo et al. [31] employed the Euler equations to calculate the nonbreaking solitary wave forces on slender piles. The governing equations were solved by the Finite Volume Method (FVM) and the free surface was tracked by the Volume of Fluid (VOF) method. Zhao et al. [32] carried out numerical simulations of the solitary wave scattered by a circular cylinder group based on the generalized Boussinesq equations together the FEM. Zhong and Wang [33,34] used the FEM to investigate the problem of solitary wave interaction with cylindrical structures. Cao and Wan [35] took into account the viscosity of the fluid and used the Reynolds-Average Navier-Stokes (RANS) model. The first order solitary wave was used as the incoming wave for the above simulations apart from that by Mo et al. [31], where the second order solitary wave was adopted. Isaacson [36] considered the case of a free floating cylinder and the first order solitary wave was used as the incident wave. However only vertical motion was considered and limited data were provided.

In the above work, the cylinder is fixed apart from that in Isaacson [36]. The present work aims to provide new some insight into this type of interaction based on the fully nonlinear solitary wave and with extensive results. An initially vertical cylinder is placed in the wave and it will be free to respond to wave excitation and be set into motion which will further lead to wave radiation. The numerical model for this complete wave/body interaction process is based on a time-domain higher-order boundary element method [5]. The 4th-order Runge-kutta method is used for the time step marching on the free surface in the Lagrangian framework. By means of the auxiliary function method [37], the fully nonlinear mutual dependence of fluid flow and structure motions is resolved. The accuracy of the present numerical model is verified by comparing wave propagation of a solitary wave with the fully nonlinear solution from Clamond and Dutykh [22]. Further comparison is made with the third order analytical solution and the published numerical results for the reflection of a solitary wave. Simulations are then made for solitary wave interaction with a truncated cylinder. The results are provided for motions, run-ups and forces on the cylinder.

2. Mathematical model and numerical procedure

The problem of wave interaction with a vertical cylinder in water of depth d is sketched in Fig. 1. Two right-handed Cartesian

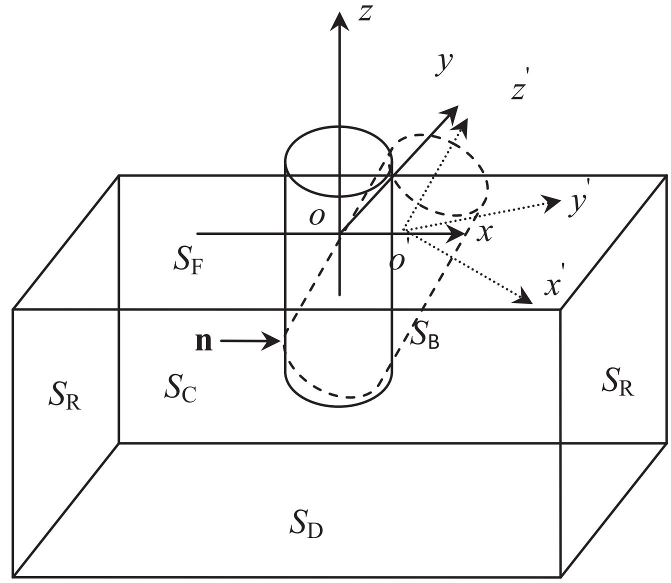

Fig. 1. Sketch of coordinate systems and computation domain.

coordinate systems are defined. One is the space-fixed system *oxyz* with the *oxy* plane on the undisturbed free surface and the z-axis pointing upwards. The other is a body-fixed system $o'x'y'z'$ with its origin o' placed at the centre of mass of the body. When the body is at its equilibrium position, these two sets of coordinate systems are parallel to each other. The centre of mass is located initially at $\mathbf{X}_{c0}$ in the space-fixed coordinate system, and $\mathbf{X}_c(=\mathbf{X}_{c0}+\boldsymbol{\zeta})$ subsequently. Here $\boldsymbol{\zeta}=(\zeta_1, \zeta_2, \zeta_3)$ is introduced to denote the translational displacements of the mass centre in the x, y and z directions respectively. The rotation of the body is defined through the usual Euler angles $\boldsymbol{\theta}=(\alpha, \beta, \gamma)=(\zeta_4, \zeta_5, \zeta_6)$, to illustrate the displacements in roll, pitch and yaw, the terms commonly used in the naval architecture.

Based on the assumption that the fluid is ideal and incompressible, and flow is irrotational, the velocity potential $\phi(x, y, z, t)$ can be introduced, which satisfies the Laplace equation in the fluid domain R

$$\nabla^2\phi = 0 \tag{1}$$

It is subject to various conditions on the instantaneous boundary S of the fluid domain, which includes the free surface S_F, the body surface S_B, the side surface S_C away from the body in the y direction, the seabed surface S_D as well as the left and right side surface S_R away from the body in the x direction. At S_C, S_D and S_R, the impermeable condition is given, that is $\partial\phi/\partial n=0$. On the free surface S_F, the fully nonlinear kinematic and dynamic boundary conditions can be given in the following Lagrangian form

$$\frac{D\mathbf{X}}{Dt} = \nabla\phi \tag{2}$$

$$\frac{D\phi}{Dt} = -g\eta + \frac{1}{2}\nabla\phi\cdot\nabla\phi \tag{3}$$

where g represents the acceleration due to gravity, $\mathbf{X}=(x, y, z)$ denotes the position vector of a fluid particle on the free surface, η is the elevation of water surface measured from its mean level, $\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla$ is the total derivative with $\mathbf{u}$ being the velocity of the fluid particle. The boundary condition on the body surface S_B is

$$\frac{\partial\phi}{\partial n} = \mathbf{V}\cdot\boldsymbol{n} \tag{4}$$