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Fully nonlinear wave interaction with freely floating non-wall-sided structures

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ABSTRACT

A fully nonlinear numerical model for a floating body in the open sea has been developed based on velocity potential together with a higher-order boundary element method (BEM). 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 mesh is generated only once at the initial time and the element nodes are rearranged subsequently without changing their connectivity by using a spring analogy method. Through some auxiliary functions, the mutual dependence of fluid/structure motions are decoupled, which allows the body acceleration to be obtained without the knowledge of the pressure distribution. Numerical results are provided for forces and run-ups of a fixed cylinder with flare and the comparison is made with the second order theory in the frequency domain. Simulations are also made for a freely floating body responding to wave excitation. Resonance related to ringing excited by the high order force at the triple wave frequency is discussed. Further results are provided for motions, forces and run-ups of a floating cylinder with flare. Comparison with the results for the fixed body and body in single degree of freedom is made.

1. Introduction

As activities in ocean engineering are moving into deeper and deeper water regions, platforms face more and more hostile wave loading. This makes accurate prediction of interactions of steep waves with a structure become more and more important. One of the major challenges in this problem is to accurately prescribe an incoming wave and the incident velocity field based on the governing equation and fully nonlinear dynamic and kinematic conditions on the moving free surface. This is further complicated by the fact that in a numerical simulation, a computational domain has to be finite and truncated at a certain distance from the structure. At the truncated boundary, it is important to ensure the wave generated by the presence of the structure and its motion not to be reflected back to computational domain, or this wave will be absorbed at the truncated boundary through a numerical boundary condition. This disturbed wave is, however, fully coupled with the incoming wave in the fully nonlinear problem. It is not straightforward to absorb the disturbed wave and at the same time not to affect the incoming wave in this fully coupled system. One way to resolve this is to mimic what is done in a physical laboratory. A numerical model is set up with a wave maker at one end and a wave absorbing beach at the other end, as well as walls on two sides. A body is then placed in the tank and the whole simulation starts when the wave maker starts motion. The finite element method (FEM) method has been extensively used in a wide range of problems, including fixed cylinders [1], vertical cylinders and a simplified floating production, storage and off-loading (FPSO) vessel only in surge motion [2], a non-wall-sided structure which is fixed or in forced surge or heave motion [3], an array of fixed cylinders [4], a SPAR platform, a barge-type floating body and one or two Wigley Hulls with motions of six degrees of freedom in head seas or in oblique waves [5], two 3D floating structures in close proximity with motions of six degrees of freedom [6]. The BEM method has also been widely used. Liu et al. [7] have investigated the bow waves generated by an advancing ship. Yan and Liu [8] considered wave–wave and wave–body interactions. Bai and Eatock Taylor [9,10], and Bai et al. [11] studied wave interactions with a fixed cylinder, a fixed and freely floating structure with flare, and an array of fixed cylinders, respectively. Mola et al. [12] considered unsteady and nonlinear ship–wave interaction. While this model reflects the experimental practice well, it has similar problems as a physical tank when modelling the true ocean environment in the open sea, principally due to side wall effect.

Ferrant [13] proposed a model for the open sea, where the total potential is split into the incident potential and the disturbed

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potential. Similar models have been used by Ferrant [14], Ferrant et al. [15], and Ducrozet et al. [16]. In this work we adopt the technique of Ferrant [13] to split the total potential, and a mixed Eulerian–Lagrangian (MEL) technique is used to track the free surface in place of semi-Lagrangian formulation adopted by the above models [13–16]. Simulations will then be made based on this model aiming to obtain insight into the interactions of steep waves and a structure with non-wall-sided water plane or a structure with a flare.

The nonlinear problem of wave interaction with a structure is also often solved based on the perturbation method. The second-order analysis can be found in many publications both in the frequency domain [17,18] and the time domain [19,20]. The results have provided important information for the slowly varying drift force at difference frequency and the springing force at sum frequency. The third-order analysis in the perturbation method is also often used. Typical examples include that by Faltinsen et al. [21] for a slender cylinder in long waves and that by Malenica and Molin [22] for a cylinder in finite water depth. Teng and Kato [23] also calculated the 3rd-order triple-frequency wave load on fixed axisymmetric bodies by monochromatic waves. The results from the third-order analysis are highly relevant to the phenomenon of “ringing”. It is a relatively large motion of the structure at a relatively high frequency. Ringing is more likely to be excited by a higher mode in the perturbation theory, because it corresponds to a higher frequency. However, the importance of the higher modes diminishes gradually in moderate waves. As a result ringing of a structure typically occurs when its frequency is about three to five times of the incoming wave frequency. Thus it is most likely to be excited by the third order force at the triple frequency.

Perturbation theory is valid only for moderate waves. In deep seas, an offshore structure or a ship is designed to operate in a very hostile environment. This makes the present fully nonlinear theory more imperative. To highlight the effect of nonlinearity, we shall apply the developed method for a non-wall-sided body. As stated in Wang et al. [3], the presence of the flare makes the simulation more complicated. The projection of the waterline on a horizontal plane varies with time because of the flare. This requires mesh regeneration to be more flexible and be able to deal with arbitrary shapes efficiently. The flare could also cause a rapid variation in pressure and velocity. This will require finer mesh and small time step if the same accuracy as that for the wall sided structure is desired. Because of these reasons, there has been far less work on wave interactions with 3D non-wall-sided structures based on the fully nonlinear model. Wang et al. [3] have investigated wave diffraction and radiation by flared structures, where the flared surface was generated by an inclined straight line from the calm water plane, and the body has constant cross section in its lower part. Bai and Eatock Taylor [10] calculated the wave interactions with fixed and freely floating structures with flare of curvature.

In this paper, a nonlinear decomposition method is adopted to solve the problem of wave–body interactions in the open sea. The whole wave elevation and the whole velocity potential are separated into two parts, mathematically. One part is the extension of the solution for the incident potential defined below the incident wave to below the total wave elevation, and the remaining part is a potential satisfying the Laplace equation and the required boundary conditions. The problem is solved by using a time-domain higher-order boundary element method. 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 [24], the fully nonlinear mutual dependence of fluid flow and structure motions are resolved. The accuracy of the present numerical model is verified by comparing the wave run-ups and motions of a vertical cylinder with the published results. Further comparison is made with results from the second-order frequency domain theory for a fixed cylinder with flare. Simulations are then made for wave interaction with a freely floating flared structure. The resonance related to ringing excited by higher order force at triple frequency is investigated. The results are provided for motions, forces and run-ups of a floating cylinder with a flare and comparison with the results for the fixed body and body in single degree of freedom is carried out.

2. Mathematical formulation

2.1. Boundary value problem

To demonstrate the three-dimensional wave interaction with bodies in an open sea with the water depth d, two right-handed Cartesian coordinate systems are defined as shown in Fig. 1. One is a space-fixed coordinate system $oxyz$ with the oxy plane on the mean free surface and with the z-axis being positive upwards. The other is a body-fixed coordinate 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. 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 in the x, y and z directions respectively, and the Euler angles $\boldsymbol{\theta}=(\alpha, \beta, \gamma)=(\zeta_4, \zeta_5, \zeta_6)$ is defined to illustrate the angles of roll, pitch and yaw, the terms commonly used in the naval architecture. The relationships between the two coordinate systems can be written as

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_{c0} \\ y_{c0} \\ z_{c0} \end{pmatrix} + \begin{pmatrix} \zeta_1 \\ \zeta_2 \\ \zeta_3 \end{pmatrix} + [C] \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} \tag{1}$$

where [25]

$$[C] = \begin{bmatrix} \cos\beta\cos\gamma & -\cos\beta\sin\gamma & \sin\beta \\ \sin\alpha\sin\beta\cos\gamma + \cos\alpha\sin\gamma & -\sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & -\sin\alpha\cos\beta \\ -\cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & \cos\alpha\sin\beta\sin\gamma + \sin\alpha\cos\gamma & \cos\alpha\cos\beta \end{bmatrix}$$

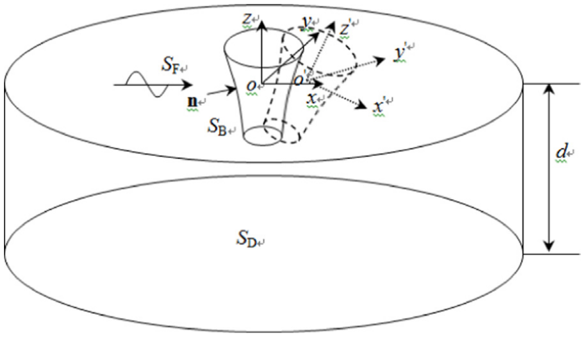

Fig. 1. Sketch of coordinate systems and computation domain.