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Fully nonlinear numerical investigation on hydroelastic responses of floating elastic plate over variable depth sea-bottom

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A B S T R A C T

The time domain fully nonlinear analysis techniques are widely recognized as the unique approach to predict accurate transient behaviors and nonlinear characteristics of the VLFS (very large floating structure). However, these complex issues have not been perfectly solved due to some considerable factors, i.e. wave nonlinearity, displacement nonlinearity, and topography nonuniformity. In this paper, a 2D (two-dimensional) fully nonlinear NWT (numerical wave tank) is developed to investigate the interaction of a monochromatic wave with a floating elastic plate over the variable depth sea-bottom by using the HOBEM (higher order boundary element method). An Euler-Bernoulli-von Karman nonlinear beam model is applied to determine the fluid pressure imposed on the fluid-structure interface. Considering computational cost, the modal functions of a beam with free ends are introduced to approximate the plate displacement. The present model is validated against existing numerical and experimental results for elastic plate placed over flat sea-bottom and wave passing over a submerged object. Numerical calculations are conducted to obtain the hydroelastic higher harmonics and displacement nonlinearity of the elastic finite plate placed over various the trapezoid-shaped sea-bottoms with different shapes and arrangements. The effects of water depths, incident wave amplitudes and incident wave periods on the nonlinear responses of the plate are further emphatically examined.

1. Introduction

Very large floating structures (VLFSs) such as floating airports, oil storage facilities, floating piers and floating performance stages have been gradually used in ocean engineering due to their powerful abilities of exploiting ocean resources and utilizing ocean space. The horizontal lengths of VLFSs can be several hundred meters to several kilometers whereas the thickness is only several meters. Owing to the very great ratio of the horizontal scale relative to the vertical scale, the VLFS response in the vertical direction cannot be assessed only by its rigid-body motions. It is therefore necessary to accurately estimate the

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hydroelastic interaction between its elastic deformation and the fluid flow field around it when designing the structure. In addition, VLFSs are usually modeled as thin elastic plates with zero draft.

Extensive researching works have been performed on the hydroelastic responses of VLFS, experimentally and numerically. Watanabe et al. [1], Eatock [2] and Chen et al. [3] presented a review of these methods on the simulation of hydroelastic responses of VLFS. One approach to tackle this problem is to use the frequency domain method, which can be found in the studies by Gao et al. [4], Utsunomiya and Watanabe [5], Utsunomiya et al. [6], Yoon et al. [7], Cheng et al. [8], Karmakar and Guedes Soares [9], Riyansyah et al. [10] and Zhao et al. [11]. These studies were mainly concerned on the 2D [9–11] or 3D [4–8] hydroelastic response amplitude operator (RAO) of VLFS and pertinent response parameters in a steady state condition. However, when considering the transient phenomena and nonlinear factors i.e. instantaneous free surface and nonlinear body surface, another time domain method is necessary to be conducted for the VLFS design. The conventional time domain approaches commonly contains the direct domain method [12–15] and the Fourier transform method [16–18]. The former approach requires that the boundary integral equation and structural equation of motion are directly discretized in time domain, whereas the latter approach produces the time-domain hydrodynamic coefficients by employing the Fourier transformation of the frequency-domain hydrodynamic coefficients. These numerical solutions were all developed by means of the boundary element method (BEM), the finite element method (FEM) and hybrid finite element-boundary element (FE-BE) method based on the linear fluid potential theory and linear structural representations. Wantanabe et al. [12] and Qiu and Liu [13,14] applied the FEM to transient behavior of a VLFS subjected to unsteady external loads e.g. vertical impact loads, airplane takeoff and landing loads. However, the response analysis is required for a few seconds and this simulation model is greatly simplified in the treatment of structure or fluid. Kashiwagi [16,17] developed an indirect time domain method based on an BEM scheme for calculating transient responses of a VLFS under dynamic load action, in which memory effects in hydrodynamic loads are taken into account through the convolution integral over the previous fluid motion. Endo [18] numerically investigated the structural loads induced by the simultaneous actions of aircraft takeoff/landing and incident regular waves by use of the hybrid FE-BE method. Cheng et al. [15] used a full time domain analysis program to study the effectiveness of the non-perforated, perforated and their combination anti-motion plates in reducing the hydroelastic responses of the VLFS.

The above mentioned studies provide enlightening contributions in the research activities related to time domain hydroelastic analysis of VLFS but their linear simulation that did not account for the wave nonlinearities, wave-wave interactions, or water depth effects is no long reliable enough for large amplitude waves and body motion and usually leads to conservative results. Recognizing the importance of this problem, some researchers have devoted significant efforts to the development of 2D [19,21,22] and 3D [20] nonlinear coupled analysis models. Liu and Sakai [19] investigated the interaction of regular waves, random waves and solitary waves with a pontoon-type VLFS by satisfying the second order continuity of the pressure and displacement on the fluid-structure interface, respectively. Kyoung et al. [20] employed FEM to simulate the hydroelastic deformation of VLFS with fully nonlinear free-surface conditions. Mollazadeh et al. [21] and Mirafzali et al. [22] adopted the meshless numerical method to calculate hydroelastic responses of fully nonlinear water waves with both semi-infinite and finite horizontal floating plates. But as noted, these mesh and meshless based methods are either still time-consuming or challengeable for determining the number of repeated knots. On the other hand, previous studies in general are concerned with the case of flat-bottom base surface. In certain conditions, the VLFS may be anchored at some reefs through a mooring system. Therefore, it could be computationally more accurate, and physically realistic, to model problems as the problem as a VLFS floating on the sea of varying depth. This is the motivation for the present work. In this paper, the elastic floating plate and the variable depth sea-bottom are considered as a strip and the wave crest is parallel to the strip. Therefore, the 2D nonlinear interaction between regular waves and a floating elastic plate placed over non-uniform topography is investigated through fully nonlinear numerical wave tank (NWT). The numerical model is established by an efficient higher order boundary element method (HOBEM), which as an effective tool has been successfully applied to obtain a fully nonlinear NWT in the last two decades (see these papers given by Kim and Kim [23], Fochesato et al. [24], Ning and Teng [25], Zhou et al. [26], Ning et al. [27], Lin et al. [28]). In contrast to the FEM, the HOBEM can clearly reduce the original n-dimensional computational domain to an (n-1)-dimensional partial differential equation, and continuous regeneration of the mesh is more efficient and powerful for time domain simulation.

Based on the theory of Ning et al. [27], in this paper a robust numerical model is proposed to analyze the hydroelastic responses of a floating elastic plate on the sea of depth-varying seabed. The arbitrary input waves are generated by the submerged sources distributed inside the fluid domain, in which a staring ramp is carried out in order to reduce the repeated reflection disturbances of incident boundary. An artificial absorbing layer is installed at end-wall to minimize the surface wave reflection. An image Green function [28] in finite water depth is used so that the flat bottom surface is excluded from the integration domain. The temporal free surface is updated at each time step based on the 4th order Runge-Kutta scheme and the mixed Eulerian-lagrangian (MEL)-material-node time marching technique. The vertical displacement of the fluid-structure interface is expressed by a superposition of modal functions with generalized unknown coordinates. The natural modes [29] of a beam with free ends are adopted as appropriate modal function, and thus the gradient of the plate surface can be quickly obtained once the generalized unknown coordinates are solved at each time step. As compared with the interpolating method of RBF-type artificial neural network [21,22], the modal expansion method can clearly reduce the number of unknowns which can be obtained directly from a solution of homogeneous equations by employing the Galerkin scheme at each time step. Mesh regeneration and interpolation are applied on the free surface and fluid-structure interface to suppress possible numerical instability.