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Stochastic hydroelastic analysis of a very large floating structure using pseudo-excitation method

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ABSTRACT

This paper is concerned with the linear hydroelastic response of a pontoon-type very large floating structure (VLFS) in short-crested irregular waves. The linear potential theory is employed for the analysis of VLFS in frequency domain. To decouple the fluid–structure interaction, the higher-order boundary element method (HOBEM) combined with the finite element method (FEM) is adopted. VLFS is modeled as a Mindlin plate, and the mode superposition method is used to reduce the dimension of dynamic equations. The pseudo-excitation method (PEM) is adopted to analyze the stationary stochastic response of the floating structure. The efficiency of this new calculation scheme with the application of PEM is investigated in comparison with the conventional method for stochastic response by analyzing the computational complexity theoretically. Finally, the new calculation scheme is validated by comparing with the experimental data as well as the existing numerical results calculated in the conventional way. In addition, the efficiency of the present numerical approach is also testified which indicates that the proposed numerical scheme is time-saving.

1. Introduction

The very large floating structure (VLFS) is able to expand the living space for human beings. In contrast to the land reclamation from the sea, VLFS has less impact on the surrounding ecosystem and costs less. Because of the advantages above, VLFS has been applied to floating bridges, floating piers, floating fuel storage facilities, and the floating airport model Mega-Float, etc. [1].

Generally, the height of VLFS is only a few meters, which is much smaller than its horizontal dimensions. Therefore, VLFS is usually modeled as a floating plate for simplicity, and it is necessary to consider the hydroelasticity of the structure, which allows for the interaction between the floating elastic body and water waves. Most hydroelastic analyses of VLFS are carried out in regular waves in frequency domain. For linear hydroelastic analyses, the hydrodynamic loads and the dynamic response of the floating structure can be dealt with separately, i.e., firstly the hydrodynamic pressure on the floating structure is generally solved by the boundary element method (BEM), and then the response of the floating structure under the pressure is calculated. Several methods have been used to deal with the deformation of the structure, including the Galerkin method [2,3] combined with the “generalized mode” proposed by Wu [4] and Newman [5], and the mode superposition method consisting of the wet mode approach [6] and the dry mode approach [7,8], of which the dry mode is obtained by the finite element method (FEM). Different from the methods above, Meylen [9] proposed a variational equation for a floating thin plate subjected to wave forces, which combines the variational equation of the plate with the free-surface Green function method together. BEM can generate an unsymmetrical full matrix, which is difficult to deal with. In addition, irregular frequencies are present if the free-surface Green function is used. Therefore, some other methods are proposed for solving the fluid motion around VLFS, including FEM [10,11] and the hybrid finite/infinite element method [12]. However, it is difficult to analyze the hydroelasticity of VLFS using BEM or FEM for the huge horizontal dimensions of the floating structure. Therefore, analytical methods, and semi-analytical methods using eigenfunctions have been widely used for the study of pontoon-type VLFSs of simple geometries and small drafts [13–16], as these methods are less time-consuming and more efficient in the parametric study of the hydroelastic response. In recent years, several computer codes for the hydroelastic analysis of VLFS have been developed, and a detailed comparative study of the simulation results from them was carried out by Riggs et el. [17].

In general, the floating bodies in actual engineering are of complex geometries; in this case, the conventional BEM is generally employed for the hydrodynamic computation of VLFS, but the required computations are extremely huge. To deal with the problem in the computation, some studies of efficient computation

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have been carried out. Wu et el. [18] proposed the double composite singularity distribution method for the hydroelastic analysis of a floating structure which has two planes of symmetry and nearly 75% of the total equations can be reduced. Wang et el. [19] introduced a cut-off criterion for the Green function and its derivatives to convert full matrices formed by BEM into sparse matrices, and then applied an iterative sparse solver to the calculation of sparse matrices to reduce the CPU time. Kashiwagi [3] adopted bi-cubic B-spline functions to represent the unknown pressure, and employed "relative similarity relations" to evaluate the coefficient matrix formed by the pressure-distribution method, which can reduce the computational time drastically with a small number of unknowns required only. Recently, another two fast algorithms, namely the pre-corrected Fast Fourier Transform (pFFT) method and the fast multipole method (FMM), have been applied to the acceleration of BEM and make it possible to study the hydrodynamics of large floating structures of general geometries. The pFFT method has been applied to the analysis of the Mobile Offshore Base (MOB) [20,21] and can reduce the computational time and memory cost for BEM from the order $O(N^2)$ to $O(N\log N)$. Utsunomiya et el. [22,23] have developed another form of the higher-order boundary element method (HOBEM) accelerated by FMM, which can reduce the storage requirement and CPU time to $O(N)$ and $O(N\log N)$, respectively.

Some investigations have been carried out on the stochastic hydroelastic analysis of VLFS for a reliable design, which will be subjected to irregular waves during its whole service life. Hamamoto [24] analyzed the stochastic response of a circular floating island subjected to wind-induced waves under both long-term and short-term descriptions of loadings, of which the short-term description of external loadings was represented by spectral density functions. Chen et al. [25,26] carried out the research on the second order response of VLFS induced by coupling of first-order wave potentials or the membrane force of the plate in multidirectional irregular waves. Ertekin et el. [27] investigated the hydroelastic response of a pontoon-type VLFS sheltered by a breakwater in regular and irregular waves based on the linear Green–Naghdi theory and the eigenfunction-expansion matching method. Using the same method as Ref. [12], Miyajima et el. [28] analyzed the hydroelastic response of the Mega-Float Phase-II model in short-crested irregular waves and compared their results with the measured values. Refs. [27,28] adopted the formula for linear systems of single degree of freedom (SDOF) to evaluate the response spectrum of VLFS, which means that the cross-correlation between responses of any two points of the floating structure is neglected, and only approximate results can be obtained in this way. Recently, Papaioannou et el. [29] studied the linear stochastic response of VLFS subjected to a directional wave spectrum by the stationary random vibration theory, which is an accurate method to the stochastic analysis of systems of multiple degrees of freedom (MDOF) without any cross-correlation terms neglected.

However, the response spectra of VLFS are quite difficult to calculate due to the computations of $O(N^3)$ by the stationary random vibration theory, in which case the required number of unknowns N is huge. In recent years, Lin et el. [30,31] have developed the pseudo-excitation method (PEM), which is efficient in dealing with stochastic responses of linear systems of large degrees of freedom, and has been applied to stochastic analyses of long-span bridges, high-speed trains [32], and the fatigue damage of the deepwater riser [33], etc.

In this study, we adopt PEM to study the linear hydroelasticity of a pontoon-type VLFS subjected to short-crested irregular waves in frequency domain. VLFS is modeled as a Mindlin plate with allowance for the effect of transverse shear deformation and rotary inertia. The fluid motion is solved by HOBEM, and the deformation of the floating structure is calculated by the mode superposition method, of which dry modes of the structure obtained by FEM are chosen. A directional wave spectrum is used for the short-term description of short-crested irregular waves. The efficiency of this calculation scheme with the application of PEM is discussed theoretically and verified by a numerical example at the end of this paper. Finally, the accuracy of the present method is also verified by comparing our numerical results with the experimental data as well as the existing numerical results obtained by the stationary random vibration theory. Some meaningful conclusions about the present calculation scheme are proposed.

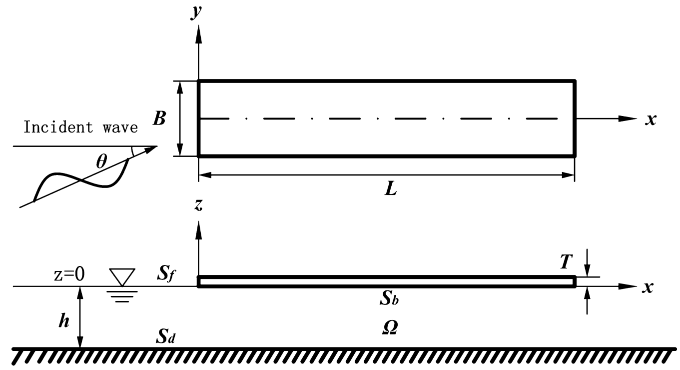

Fig. 1. The schematic diagram of the fluid–structure interaction problem.

2. Hydroelastic analysis of VLFS

In this section, the linear hydroelasticity of VLFS in regular waves is analyzed in frequency domain. The schematic diagram of the fluid–structure interaction problem is shown in Fig. 1. The pontoon-type VLFS is defined with length L, width B, height T, and modeled as a floating plate assumed to be flat with free edges. A zero-draft assumption is adopted for simplicity. The symbols Ω, S_f, S_b and S_d denote the fluid domain, the free surface, the bottom surface of the structure and the flat seabed, respectively. Three-dimensional Cartesian coordinate system o-xyz is established with o-xy plane coinciding with the undisturbed free surface and z-axis orienting positively upwards.

2.1. Equations of motion for the plate

The height of VLFS is much smaller than its length and width, so the floating structure is usually modeled as a Kirchhoff plate which does not allow for transverse shear deformation. It is accurate to use the Kirchhoff plate theory when the plate is homogeneous and thin, in which case the effect of shear deformation is of no significance. However, if VLFS consists of different kinds of materials which behaves like sandwich plates, the effect of shear deformation cannot be neglected. In addition, when analyzing the wave-induced transverse shear force of VLFS, Gao et al. [8] found that the maximum shear force obtained by the Mindlin plate theory is about 10% larger than the one by the Kirchhoff plate theory. Therefore, in this study we model VLFS as an isotropic Mindlin plate for a more accurate evaluation of shear forces of the structure.

The displacements of a Mindlin plate are given as [34]

$$U_P(x,y,z,t) = z\Theta_y(x,y,t) \tag{1a}$$

$$V_P(x,y,z,t) = -z\Theta_x(x,y,t) \tag{1b}$$

$$W_P(x,y,z,t) = W(x,y,t) \tag{1c}$$

where U_P, V_P, and W_P denote the displacements along x-axis, y-axis, and z-axis, respectively. Θ_x, Θ_y represent the rotations about x-axis and y-axis, respectively, and W is the vertical displacement of the neutral surface of the plate.