Journal of Fluids and Structures ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

A discrete-modules-based frequency domain hydroelasticity method for floating structures in inhomogeneous sea conditions

Wei Wei [a,b], Shixiao Fu [a,b,*], Torgeir Moan [c], Ziqi Lu [a], Shi Deng [c]

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, China
[b] Collaborative Innovation Centre for Advanced Ship and Deep-Sea Exploration, Shanghai, 200240, China
[c] Norwegian University of Science and Technology, Trondheim, Norway

ARTICLE INFO

Article history:
Received 25 August 2016
Received in revised form 4 May 2017
Accepted 7 June 2017
Available online xxxx

Keywords:
Inhomogeneous wave field conditions
Stiffness matrix
Discrete-modules-based method
Hydroelastic responses
Wigley hull

ABSTRACT

Based on the three-dimensional (3D) potential theory and finite element method (FEM), this paper proposes a new numerical method for hydroelastic predictions of floating structures in inhomogeneous seabed and wave field conditions. The continuous floating structure is first discretized into rigid modules connected by elastic beams. The motion equations of the entire floating structure are established according to the six degrees of freedom (6DOF) motions of each module by coupling the hydrodynamics of the modules with the structural stiffness matrix of the elastic beams in the frequency domain. By applying different wave excitation forces onto different modules, this discrete-modules-based method then uniquely realizes application of various wave excitation forces onto different modules of the structures in inhomogeneous waves. The hydroelastic responses of a plate and a Wigley hull under an even and uneven seabed using the proposed method are verified against the results from the published model tests and the conventional 3D hydroelastic method. Finally, the effects of inhomogeneous waves on the distributions of the bending moment, shear force and vertical displacements of the freely floating plate are investigated. The results show that the inhomogeneity of waves may induce about 2∼3 times increase of the force responses in a specific wave frequency.

1. Introduction

Since the late 1970s, hydroelasticity theory has been developed from 2D (Betts et al., 1977; Bishop et al., 1979) to 3D (Lee et al., 2015; Shin et al., 2015; Taghipour et al., 2009; Wu, 1984) and from linear (Bishop et al., 1986; Ohkusu and Namba, 2004) to nonlinear (Hu et al., 2012; Lee and Lee, 2016; Malenica and Tuitman, 2008; Wu et al., 1997). This theory has been widely applied in the design work of large-scale vessels and very large floating structures (VLFS') (Chen et al., 2006).

Two hydroelasticity approaches have been employed for the hydroelastic analysis of floating structures on an even seabed and in homogeneous wave conditions: the modal superposition method and direct method (Loukogeorgaki et al., 2012). Depending on the method used to obtain the structural modes, the modal superposition method can be further divided into the "dry" mode method (Senjanović et al., 2008a, b) and the "wet" mode method (Humamoto and Fujita, 2002; Loukogeorgaki et al., 2012; Michailides et al., 2013). When it comes to the joining forces of the connectors of the interconnected floating structures, the local deflection/motion modes of the connectors have to first be calculated or

* Corresponding author at: State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, China.
E-mail address: shixiao.fu@sjtu.edu.cn (S. Fu).

http://dx.doi.org/10.1016/j.jfluidstructs.2017.06.002

predefined (Fu et al., 2007; Gao et al., 2011; Lee and Newman, 2000; Michailides et al., 2013; Newman, 2005), which sometimes becomes very hard or even impossible because of the strong coupling of the global deformation modes of the floating structures.

The direct method can analyze structures whose modes cannot be easily established using the full modes of the discretized system. Kim et al. (2007) and Yoon et al. (2014) combined the higher-order boundary element method (HOBEM) with the finite element method (FEM) and simplified the connectors as spring elements and plate finite elements, respectively, acquiring the hydroelastic responses of a multi-module VLFS and the joining forces in the connectors. Meanwhile, the direct method has been applied to the hydroelasticity of floating structures with liquid tanks by considering the couplings among structural motion, sloshing and waves (Lee et al., 2015).

The hydroelastic responses of floating structures in a uniform water depth were the main considerations in the above mentioned research. However, the effects of coastlines (Xia et al., 1999), seawalls (Ertekin and Kim, 1999) and varying sea bottom topographies (Utsunomiya et al., 2001) on the hydroelastic responses of nearshore structures have been recognized as important issues in recent decades. Numerical methods for the hydroelastic responses of floating structures in variable bathymetry regions have been developed (Murai et al., 2003). Kyoung et al. (2005) investigated the effect of various sea-bottom topographies on the hydroelastic responses by adopting the FEM in a fluid domain. Song et al. (2005) used the boundary integral method of the finite water depth Green's function and the plate theory to analyze the vertical displacements of a VLFS model on an uneven sea bottom and verified that the uniform effect of the seabed should be considered in the hydroelastic analysis. Gerostathis et al. (2016) extended the coupled-mode model that was developed by Belibassakis and Athanassoulis (2005) to the hydroelasticity of structures with shallow drafts lying over variable bathymetry regions.

In addition to a complex seabed profile, the influences of the inhomogeneity of the incident waves (spatially varying incident wave angles and wave parameters) on the hydroelasticity have been considered during the design of large horizontal-scale structures near an island or in a fjord (Ding et al., 2016; Lie et al., 2016).

Based on the recently developed method (Lu et al., 2016), a new numerical method is established for the prediction of the hydroelastic behaviors of floating structures in both homogeneous and inhomogeneous seabed and wave field conditions. This method is verified against the model tests and the conventional 3D hydroelastic method. The effects of the uneven sea bottom and the influences of inhomogeneous regular waves on the hydroelastic responses are investigated in numerical examples. The inhomogeneity of waves may induce a 30%–80% increase in the force responses, which should be considered in hydroelastic analyses.

2. Theoretical background

Fig. 1 provides an overview of the discrete-modules-based hydroelastic analysis process. The floating structure is first discretized into a set of rigid modules that are connected by elastic beams. Considering the hydrodynamic interactions between modules, the multi-body hydrodynamic theory is adopted to obtain the velocity potential of the flow field (the incident potential ϕ_I, the diffraction potential ϕ_D and the radiation potential ϕ_R) and the wave excitation force f_w, added mass A and damping coefficient C of various modules. The motions of each module are affected by the hydrodynamic interactions with the surrounding modules and are restricted by the displacement continuity of adjacent modules. The displacement continuity between modules is guaranteed by establishing an elastic beam with uniform section stiffness matrix $[k]$ between the equivalent centers of the modules. The displacements can be obtained by solving the coupled kinetic equation. Then, the bending moments, shear forces and torsional moments of the floating structure are determined based on the theory of structural mechanics.

No wet panels are set on the wall sides to avoid water resonance between two modules during the hydrodynamic calculation. Thus, the modules in the middle have two vertical walls, and those in the bow and stern have three. Simultaneously considering bending and torsional deformations in three-dimensional floating structures is difficult when adopting the simulation method of the beams. Therefore, the floating structure is discretized with only one module in the transverse direction for simplicity.

2.1. Hydrodynamic analysis

2.1.1. Coordinate system

The floating structure is only discretized in the longitudinal direction, so only one module is present in the transverse direction. Three right-handed coordinate systems are introduced to describe the wave-induced motion responses of a multi-module structure system: the global coordinate system $OXYZ$, body-fixed coordinate system $o_m x_m y_m z_m$ and reference coordinate system $o'_m x'_m y'_m z'_m$ ($m = 1, 2, \ldots, N$). The global coordinate system ($OXYZ$) remains fixed in space, with OXY at the still water surface and the Z axis oriented straight up. The body-fixed coordinate system ($o_m x_m y_m z_m$) moves with the floating modules and is parallel to the coordinate axes of the global coordinate system ($OXYZ$) in its initial position. The reference coordinate system ($o'_m x'_m y'_m z'_m$) coincides with the body-fixed coordinate system ($o_m x_m y_m z_m$) in the initial stage