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A study of hydroelastic behavior of hinged VLFS

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Abstract

This paper introduces a new method to study the hydroelastic behavior of hinged Very Large Floating Structures (VLFSs). A hinged two-module structure is used to confirm the present approach. For each module, the hydroelasticity theory proposed by Lu et al. (2016) is adopted to consider the coupled effects of wave dynamics and structural deformation. The continuous condition at the connection position between two adjacent modules is also satisfied. Then the hydroelastic motion equation can be established and numerically solved to obtain the vertical displacement, force and bending moment of the hinged structure. The results calculated by the present new method are compared with those obtained using three-dimensional hydroelasticity theory (Fu et al., 2007), which shows rather good agreement.

Keywords: Hydroelasticity; VLFS; Hinged structures; Frequency domain; Multi-body

1. Introduction

Very Large Floating Structures (VLFSs) are very flexible offshore structures which are widely regarded as an alternative option of ocean space utilization. Due to their obvious advantages including environmental friendliness, easy and fast construction and removal and low cost in construction, VLFSs have been gradually designed for various applications such as floating airports, bridges, oil storage facilities and floating artificial island. Most VLFSs can be categorized into two types, i.e. single-module VLFS and interconnected multi-module VLFS. For these flexible floating structures, the coupling between structural deformation and fluid field becomes a significant factor when it comes to their dynamic response in waves. For single-module VLFSs, many theories have been proposed to predict their response (Wu, 1984; Tsubogo and Okada, 1998; Tuitman et al., 2012; Lu et al., 2016). Based on these theories, the dynamic response of various types of VLFSs has been investigated. Wu et al. (2014) calculated the hydrodynamic response of multi-leg floating structures. Pan et al. (2015) investigated the hydrodynamic response of mooring lines for a large floating structure in the South China Sea.

For hinged multi-module VLFSs, some researchers (Newman, 1994; Gou et al., 2004) studied their dynamic response by neglecting the elastic deformation of the structure. Fu et al. (2007) combined three-dimensional hydroelasticity theory and multi-rigid-body kinematics to consider the hydroelastic response of an articulated VLFS. In addition, the Mindlin plate element method was also used to obtain the hydrodynamic response of two articulated VLFSs (Kim et al., 2007; Gao et al., 2011). Riyansyah et al. (2010) used the Euler−Bernoulli beam to study articulated VLFSs without considering the effect of the floating body on the fluid.

The purpose of this paper is to propose a new method to calculate the hydroelastic response of interconnected multi-

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module VLFSs. The hinge is assumed to be rigid while each module of the VLFSs is assumed to be flexible with structural deformation considered. As a simple case, the hinged two-module VLFS model adopted by Fu et al. (2007) is used here to confirm the present method. The present approach is a combination of the hydroelasticity theory for a single-module continuous VLFS proposed by Lu et al. (2016) and hinged rigid multi-body theory. For each module, the hydroelasticity theory proposed by Lu et al. (2016) is adopted to consider the coupled effects of wave dynamics and structural deformation. At the hinged position, the method of Gou (Gou et al., 2004) is used to consider the continuous condition. Then the hydroelastic motion equation can be established and numerically solved to obtain the vertical displacement, force and bending moment of the hinged structure. All results calculated by the present approach are compared with those obtained by three-dimensional hydroelasticity theory (Fu et al., 2007).

2. Basic theory

2.1. Multi-body hydroelasticity theory

As the results calculated using the present approach are compared with those obtained by three-dimensional hydroelasticity theory proposed by Fu et al. (2007), this paper will give a brief introduction of Fu's method before we move forward to a detailed description of the present approach. For simplicity, we avoid listing many mathematical equations and introduce the main idea of Fu's method (more details can refer to Fu's paper). Actually, the approach proposed by Fu et al. (2007) is classic three-dimensional hydroelasticity theory, in which the hydroelastic response of flexible floating structures can be calculated in three main steps:

(1) Evaluation of the dry natural oscillation mode for hinged two-module flexible structure.
(2) Evaluation of the hydrodynamic coefficients (added mass, radiation damping and wave excitation force) for each mode.
(3) Solving the coupling modal equation to obtain the hydroelastic response of the hinged flexible structure.

The hydroelasticity theory for a continuous flexible structure proposed by Lu et al. (2016) is adopted in this paper. Unlike traditional three-dimensional hydroelasticity theory (Fu et al., 2007), in the approach proposed by Lu et al. (2016), the coupling between structural deformation and fluid field is considered by (imaginarily) dividing the continuous structure into several submodules and adding a virtual beam between the center of each submodule. Then multi-body hydrodynamics and beam bending theory can be combined together to deal with the dynamic response of flexible structure without considering the natural mode of the dry structure. The present work actually extends Lu's theory to deal with a more complex problem, i.e. the dynamic response of (rigidly) hinged multi-module flexible structure (not a continuous structure in the Lu's work) in waves. For the integrity of the paper, we will revisit the method of Lu et al. (2016) in this section. For the hydrodynamic aspect, this paper adopts the assumption of ideal fluid, i.e., the fluid is inviscid, irrotational, and incompressible. The incident wave amplitude is assumed to be small relative to a characteristic wavelength and body dimension, and therefore linear Airy wave theory can be applied. The hydrodynamic coefficients of the equivalent multi-module floating structures considering diffraction and radiation effects can be calculated using the conventional potential theory (In this paper, the commercial software Hydrostar is used to obtain these hydrodynamic coefficients).

Fig. 1 is a schematic of hinged multi-module flexible floating structure and its surrounding fluid field. The number of modules for the floating structure is m. Two adjacent modules are hinged together. In Lu's theory, a continuous (single-module) flexible structure is divided into several submodules to approximately consider the coupled effects of wave dynamics and structural deformation (using multi-body hydrodynamics and beam theory). So for multi-module flexible structure, each module is divided into several submodules (the number of submodules for each module is n shown in Fig. 1). Based on the assumptions of an ideal fluid and linearity, the velocity potential can be decomposed into three parts as follows:

$$\phi = \phi_{\mathrm{I}} + \phi_{\mathrm{D}} + \phi_{\mathrm{R}} \tag{1}$$

where ϕ_I, ϕ_D and ϕ_R denotes, respectively, the incident wave potential, diffraction wave potential, and radiation wave potential. The incident, diffraction potential and radiation potential satisfy the following boundary conditions:

$$\begin{cases} \nabla^2\phi = 0, & in\ \Omega \\ -\omega^2\phi + g\dfrac{\partial\phi}{\partial z} = 0, & on\ S_F \\ \dfrac{\partial\phi}{\partial z} = 0, & on\ S_B \\ \dfrac{\partial(\phi_I+\phi_D)}{\partial z} = 0, & on\ \sum_{q=1}^{m\times n} S_q \\ \dfrac{\partial\phi_{Rk}}{\partial n_k} = \overrightarrow{V}_{S_k}\cdot\overrightarrow{n}_k & on\ S_k(k=1,2,\ldots,n\times m) \\ \dfrac{\partial\phi_{Rk}}{\partial n_j} = 0 & on\ \sum_{j=1,j\neq k}^{m\times n} S_j \\ \lim_{r\to\infty}\sqrt{r}\left(\dfrac{\partial\phi_{Rk}}{\partial r} - \dfrac{i\omega^2}{g}\phi_{Rk}\right) = 0 & on\ S_\infty \end{cases} \tag{2}$$

where (see Fig. 1) Ω is the fluid domain, and S_F, S_B, and S_∞ are the free surface, bottom surface, and the boundary surface at infinity of the fluid, respectively. S_k (S_j) represents the wetted body surface of the kth (jth) submodule ($k, j = 1, 2, \ldots, n \times m$; $j \neq k$). $\overrightarrow{n}_k$ represents the outward-directed unit vector normal to the wetted surface of the kth submodule, $\overrightarrow{V}_{S_k}$ is the velocity of a given point on the wetted surface of the kth submodule,