Journal of Fluids and Structures 59 (2015) 270–284

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Nonlinear network modeling of multi-module floating structures with arbitrary flexible connections

H.C. Zhang [a], D.L. Xu [a,*], S.Y. Xia [a], C. Lu [a], E.R. Qi [b], C. Tian [b], Y.S. Wu [b]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, PR China
[b] China Ship Scientific Research Center, Wuxi 214082, PR China

ARTICLE INFO

Article history:
Received 30 March 2015
Accepted 24 September 2015
Available online 26 October 2015

Keywords:
Floating structure
Network dynamics
Flexible connector
Nonlinear dynamics

ABSTRACT

Multiple floating modules connected by flexible connectors can be viewed as a network structure. A standard modeling process for multi-module floating structures in arbitrary topology is presented by using network theory. A three-dimensional model is developed using the linear wave theory, dynamic model of single floating module, constitutive model of flexible connectors and model of a mooring system. As a typical application, a floating airport model is established and further its nonlinear dynamic responses and connector loads are analyzed. Numerical results show that the traditional linear analysis may underestimate the actual results. The methodology applied in this paper is extensible to many engineering problems with network structures alike.

1. Introduction

The needs for ocean space utilization are expected to be increasing in future according to the rapid expansion of modern industrial cities among coastal areas. Surely, very large floating structure (VLFS), which could be utilized as a floating airport, mobile offshore base, floating pier, floating plant, floating city, floating storage facility, etc., plays a great role of the utilization of ocean space because it has various merits in view points of economy, safety, and environmental friendliness (Park et al., 2004). In order to perform its various functions and meet the constraints of safety and cost, intensive efforts should be made in the initial conceptual design stage, structural arrangements, construction process and maintenance after operation (Lee and Newman, 2000; Rognaas et al., 2001; Utsunomiya et al., 2004).

Among the various fields of design technology for VLFS, it is no doubt that the safety design of floating structures based on hydrodynamic response analysis is one of the most important concerns (Du and Ertekin, 1991) particularly for some applications that require stringent tolerance on the deformation of the floating structure. For example, the maximum pitch angle between modules is less than about 0.86° for the aircraft operation on Mobile Offshore Base in Sea State 6(Rognaas et al., 2001). In the past decades, the research on VLFS involves two types of floating bodies, the box shaped pontoon type and the semi-submersible type. The hydroelastic theory has been widely applied to analyze the dynamics characteristics (Price and Wu, 1986) due to the small draft in comparison with its length for the pontoon type VLFS. The common approach is to model the entire floating structure by a single beam or plate based on the classical thin plate theory while the water wave is modeled by using the linear wave theory (Aoki, 1997; Hamamoto, 1994; Kashiwagi, 1998; Khabakhpasheva and Korobkin,

* Correspondence to: College of Mechanical and Vehicle Engineering, Hunan University, Yuelu District, Changsha City, Hunan Province, PR China. Tel.: +86 731 88821791; fax: +86 731 88822051.
E-mail address: dlxu@hnu.edu.cn (D.L. Xu).

http://dx.doi.org/10.1016/j.jfluidstructs.2015.09.012
0889-9746/

2001). For the larger draft to length ratios as opposed to the mat-like VLFS, this necessitates to model the floating structure as a thick plate by using Mindlin plate theory (Watanabe et al., 2006). The floating structures discussed above are all viewed as a single continuum structure and their responses are obtained by using the linearized modal superposition or finite element discretization method. Due to its vast scale of VLFS, a single continuum structure may cause extreme high deformation loads in the internal of the structure and may also be troublesome in construction, transportation and deployment. Thus multiple standardized modules with flexible connectors are concerned (Watanabe et al., 2004) where the connection plays an important role in dynamic responses. Maeda et al. (1979) studied the one-dimensional behavior of floating structures consisting of rigid modules with rigid or pin connectors for regular waves by a strip method. Fu et al. (2007) and Wang et al. (2009) proposed the use of hinge or semi-rigid connectors instead of rigid ones since the non-rigid connectors are more effective in reducing the hydroelastic response as comparing to the rigid connectors. Khabakhpasheva and Korobkin (2002) and Xia et al. (2000) dealt with a VLFS as two-dimensional articulated beams or plates connected by idealized connectors that are considered as two independent vertical and rotational springs. They showed that the hydroelastic response is strongly dependent on the stiffness of connectors and the incoming wave frequency. Gao et al. (2011) examined the effects of the location and the rotational stiffness of a flexible line connection on the hydroelastic response. A pontoon type floating structure (PFS) which consists of deformable floating modules connected with flexible connectors in longitudinal and (or) transverse directions is studied by Michailides et al. (2013). The effect of the connector's rotational stiffness and the grid type of the PFS on the hydroelastic response and the connectors' internal load are analyzed. The results indicated a complicated relationship between the internal load of the connectors and the hydroelastic response of the examined PFS configurations when examining the effects of the connectors' rotational stiffness and the excitation for the grid type PFS. The semi-submersible type floating structure is an optimal choice in order to reduce the hydrodynamic response in the deep sea area. To determine its hydroelastic response, it requires a structural model of VLFS considering the elasticity of the structure, and a hydrodynamic model for the fluid force. Kim et al. (1999) developed a three-dimensional hydroelastic model of a multi-module linked floating structure under regular waves with arbitrary angle by using FEM for structures and WIMIT program for the fluid where the connector is represented by a linearized stiffness matrix with respect to the displacements at the module connection points. However, the analysis for a refined finite element model is hardly executed due to the massive scale of the floating structure. Thus there is motivation to use rigid modules, flexible connector (RMFC) model (Wang et al., 1991), especially for conceptual and preliminary design. In the RMFC model, the VLFS is represented by multiple rigid modules connected by flexible connectors with assigned stiffness properties (Riggs and Ertekin, 1993). The connectors are usually modeled as simple linear and 'zero-length' springs (Riggs et al., 1998a). Paulling and Tyagi (1993) introduced a RMFC model with four modules in which each module was modeled by slender tubular members using the Morison formula and a pair of modules are connected by a combination of springs and damping devices (dashpots) to generate linear proportional forces. A comparative study of the linear wave induced response of a 5-module mobile offshore base (MOB) on two structural models (rigid module with flexible connector model and finite element shell model) is reported in Riggs et al.'s works (2000). The results showed that the simplified RMFC model can predict the response very well if the parameters correspond well to the FEM model's. Reviewing the recent research works above and many others not listed here carefully, we can conclude that almost all of the modeling methods adopt the linearization approach for the classical beam (or plate) model or FEM models for VLFS. When dealing with connector models, it is common to assume the flexible connection as independent linear springs in all degrees of freedom or discretized stiffness matrix using FEM method. This treatment ignores the effect of nonlinearity and artificially decouples the interaction of the module motions through connection points. Due to the large scale of floating modules, small motions of the floating modules may lead to large displacements at the connection points so that it could give rise to strong geometrical nonlinearities in the connector model even if the connector element possesses linear elasticity characteristics. The nonlinearity may induce a variety of complex dynamic behaviors, very different from the linear results such as response jumping, motion synchronization and phase lock among the floating modules (Xu et al., 2014a; Zhang et al., 2015a). As for topological forms, VLFS may be constructed in diverse platform shapes, such as chain-type for a floating runway (June Bai et al., 2001), rectangular-type for entertainment facilities (Koh and Lim, 2009), circular-type for an artificial island (Andrianov and Hermans, 2005). In fact, there have been few modeling works to deal with various topology structures for VLFS.

A multi-module floating structure connected by flexible connectors in a particular topology is a typical network structure where each module under the excitation of waves can be viewed as an oscillator and a connector is viewed as a coupling between the oscillators. The dynamic network theory can be utilized to model and predict the nonlinear dynamics of VLFS. Our preliminary research on two dimensional problems of a chain-type floating airport (Xu et al., 2014a, 2014b; Zhang et al., 2015a, 2015b) confirms the feasibility of the new methodology for such applications. This method showed that the nonlinear effect could significantly influence the dynamics prediction of the floating airport in which complex dynamical behaviors have been investigated, including sudden changes of module responses and connector loads (Xu et al., 2014a), the amplitude death phenomena for the global dynamic stability (Xu et al., 2014b), collectively synergistic effect of network dynamics among floating modules due to coupling (Zhang et al., 2015a). These works are the initial attempt of introducing nonlinear network dynamics theory to floating airport in marine engineering to enrich the methodology in the prediction of dynamics response of VLFS.

This paper presents a new approach for modeling three dimensional problems of VLFS in arbitrary structure topology, while the previous works (Xu et al., 2014a, 2014b; Zhang et al., 2015a) are only limited to two dimensional problems (surge, heave and pitch motions) with a chain-type platform. With the three dimensional model to be developed, one enables to