Ocean Engineering 78 (2014) 112–123

Contents lists available at ScienceDirect

Ocean Engineering

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

Hydroelastic design contour for the preliminary design of very large floating structures

Jin-Gyun Kim, Seong-Pil Cho, Ki-Tae Kim, Phill-Seung Lee *

Division of Ocean Systems Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea

ARTICLE INFO

Article history:
Received 29 January 2013
Accepted 2 November 2013
Available online 11 December 2013

Keywords:
Very large floating structures
Hydroelastic analysis
Preliminary design
Response contour
Design contour
Bending moment

ABSTRACT

In this paper, we propose a hydroelastic design contour (HDC) that can be practically used for the preliminary design of pontoon-type rectangular very large floating structures (VLFSs). Using the design contour, we can easily predict the maximum bending moment of VLFSs in irregular waves. To develop the design contour, we first construct the hydroelastic response contours (HRCs) by extensively carrying out hydroelastic analyses considering various structural and wave conditions, namely, the bending stiffness and aspect ratio of VLFSs, incident wave length and angle, as well as the sea state. Based on the pre-calculated HRCs, we develop the HDC considering irregular waves. We then propose a preliminary design procedure for VLFSs using the HDC and demonstrate the design procedure for pontoon-type rectangular VLFSs. The HDC can significantly reduce time and effort for the design of VLFSs.

1. Introduction

Very large floating structures (VLFSs) have attracted many engineers since the concept appeared in the 19th century. VLFSs can be used as platforms for various offshore facilities such as oil storages, container terminals and airports. Cost effectiveness, movability, and environmental-friendly features could be the representative advantages of VLFSs compared with land reclamation. Recently, several challenging projects to develop VLFSs have been carried out such as Mobile Offshore Base (ONR, 1997∼2000), Mega-Float (TRAM, 1995∼2001), Modular Hybrid Pier (NFESC, 1998∼2004), and Hybrid Quay Wall (KIOST, 2005–2009). However, the design procedures and regulations for the construction of VLFSs have not been well established yet.

In the design of VLFSs, hydroelastic analysis is required to evaluate the responses of the floating structures in waves because VLFSs have relatively small bending rigidity compared to the overall dimensions of the structures. Therefore, the complicated interaction between water waves and flexible structures should be appropriately considered to calculate the structural responses of VLFSs.

The fundamental theory of hydroelastic analysis was established for ship design in the 1980s (Bishop and Price, 1979). The methods of hydroelastic analysis for VLFSs have been actively studied as reviewed in ISSC (2006) and Watanabe et al. (2004). In most studies on hydroelastic analysis, VLFSs have been assumed to be relatively simple floating beam and plate structures (Kashiwagi, 1998; Khabakhpasheva and Korobkin, 2002; Kim et al., 2007; Eatock Taylor, 2007). Recently, VLFSs have been modeled as three-dimensional floating structures (Riggs et al., 2007; Kim et al., 2013). In general, fluid has been modeled by the potential fluid theory.

In hydroelastic analysis, fluid and structures should be handled together. Therefore, additional modeling effort and computational time are required. In the cross-section design of VLFSs, the maximum bending moment that occurs in VLFSs in the ranges of wave parameters should be calculated through hydroelastic analysis and compared with the bending moment capacity of the cross-section. Until the safety requirement is properly satisfied, hydroelastic analyses have to be iteratively performed under various structural and wave conditions.

For a typical design example, when the ranges of the incident wave length and angle are divided into 50 and 51 cases, respectively, 2550 cases of the hydroelastic analysis should be performed. To construct the wave spectrums for various irregular wave conditions, additional computational cost is required. Assuming that 4 design trials are necessary to satisfy the safety requirement, in total 10,200 (4×2550) cases of hydroelastic analysis should be carried out (Kim et al., 2011). Of course, it is also a difficult task for engineers to process all the data obtained in the analyses for the design purpose. This fact motivates this study.

The objective of this paper is to propose a very useful design tool, hydroelastic design contour (HDC), that can significantly reduce engineers' effort and time for the preliminary design of pontoon-type rectangular VLFSs.

In this study, VLFSs are simplified as two-dimensional floating isotropic plates instead of more realistic orthotropic plates or full

* Corresponding author. Tel.: +82 42 350 1512; fax: +82 42 350 1510.
E-mail address: phillseung@kaist.edu (P.-S. Lee).

0029-8018/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2013.11.006

three dimensional shell structures. The water depth is assumed to be infinite. We construct two types of hydroelastic response contours (HRC-I and HRC-II) to estimate the response amplitude operator (RAO) of the maximum bending moment for a given geometry and bending stiffness of VLFS. HRC-I shows the RAO of the maximum bending moment depending on wave length and angle. However, HRC-II shows the RAO of the maximum bending moment under given ranges of wave length and angle. Based on HRCs, we then construct HDC to estimate the maximum bending moment in irregular waves. The Beaufort scale and the corresponding JONSWAP wave spectrum are used to consider irregular wave effects in HDC.

The bending moments predicted by HDC can be used for the preliminary design of VLFSs. We also establish a new design procedure based on the HDC. The new design procedure can significantly reduce modeling effort and computational time in the design of VLFSs because time-consuming hydroelastic analyses do not need to be performed. We verify the design procedure and HDC by performing the preliminary designs of pontoon-type rectangular VLFSs with single and double hulls. We also test the feasibility of the HDC for finite water depth cases through numerical examples.

In the following sections, we first review the governing equations and the numerical procedure that we adopt to solve the hydroelastic problems of floating plate structures. The procedure to develop the hydroelastic response and design contours is explained in detail. We then propose a design procedure using the HDC and the preliminary designs of pontoon-type VLFSs are demonstrated. Finally, the concluding remarks are given.

2. Theoretical background

In this section, we briefly present mathematical formulations and discrete coupled equations for the hydroelastic analysis of floating plates interacting with surface regular waves. In this work, the structural motions and the amplitudes of incident waves are assumed to be small enough for the use of linear theory.

Fig. 1 shows the problem description. A plate ($L \times B \times H$) is floating on the water with draft d. The water depth h is measured from the flat bottom seabed to the free surface of calm water, and a fixed Cartesian coordinate system (x_1, x_2, x_3) on the free surface is introduced. The plate volume is denoted by V, and the fluid is bounded by the wet surface of the structure S_B, the free surface S_F, the surface S_∞ which is a circular cylinder with a sufficiently large radius R, and the flat bottom seabed surface S_G. An incident gravity wave with small amplitude a and angular frequency ω comes continuously from the positive x_1 axis with an angle θ. The basic assumptions are that the plate has homogeneous, isotropic, and linear elastic material, and the fluid flow is incompressible, inviscid, and irrotational. In addition, for simplicity, we set the atmospheric pressure to be zero.

2.1. Formulation of the floating plate

The equilibrium equations of the floating plate at time t are

$$\frac{\partial\, {}^t\sigma_{ij}}{\partial\, {}^t x_j} - {}^t\rho_s g \delta_{i3} - {}^t\rho_s\, {}^t\ddot{u}_i = 0 \qquad \text{in } {}^tV$$
$${}^t\sigma_{ij}^{t} n_j = -{}^tp\, {}^tn_i \qquad \text{on } {}^tS_B \tag{1}$$

where ${}^t\sigma_{ij}$ is the Cauchy stress tensor at time t, ${}^t\rho_s$ is the structural density at time t, ρ_w is the fluid density, g is the acceleration of gravity, ${}^tu_i$ is the displacement at time t, and ${}^tp$ denotes the total water pressure at time t. Note that ${}^tp = -\rho_w g x_3 + {}^tp_d$, in which p_d is the hydrodynamic pressure. Also, δ_{ij} is the Kronecker delta, and ${}^tn_i$ denotes the unit normal vector outward from the plate to the fluid at time t. We use subscripts i and j, which vary from 1 to 3 to

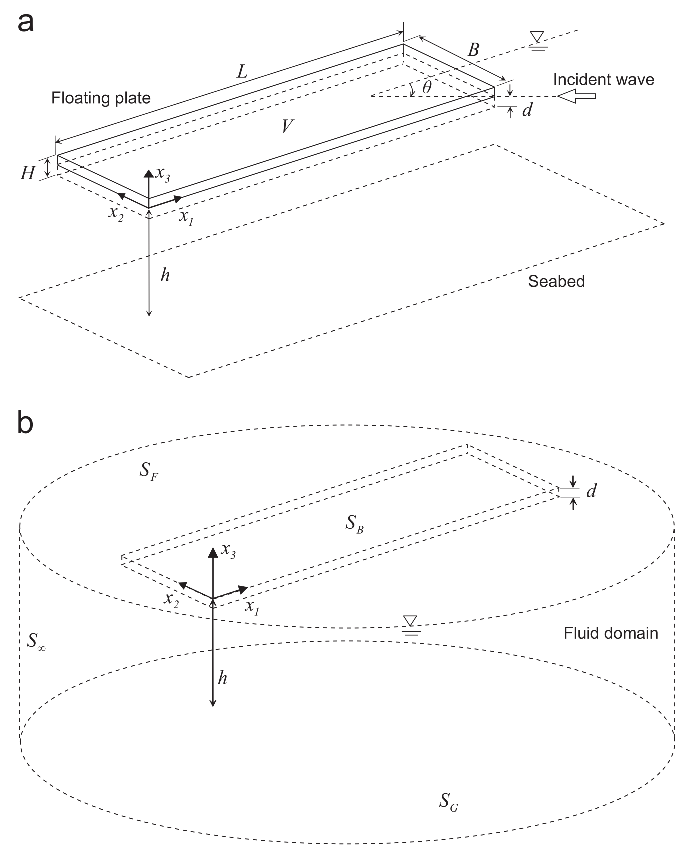

Fig. 1. Problem description for the hydroelastic analysis of a floating plate: (a) floating plate and incident wave and (b) fluid domain with an interface fluid boundary surface.

express the components of tensor, and adopt the Einstein summation convention.

The principle of virtual work for the floating plate at time t can be stated as

$$\int_{{}^tV} {}^t\rho_s^t \ddot{u}_i\, \delta u_i\, dV + \int_{{}^tV} {}^t\sigma_{ij} \delta e_{ij}\, dV$$
$$= -\int_{{}^tV} {}^t\rho_s\, g\, \delta u_3\, dV + \int_{{}^tS_B} \rho_w g\, {}^tx_3\, {}^tn_i\, \delta u_i\, dS - \int_{{}^tS_B} {}^tp_d\, {}^tn_i \delta u_i\, dS, \tag{2}$$

where δu_i and δe_{ij} refer to the virtual displacement vector and small strain tensor, respectively.

In the hydrostatic equilibrium state, which is denoted by time $t=0$, Eq. (2) becomes

$$\int_{{}^0V} {}^0\sigma_{ij} \delta e_{ij}\, dV = -\int_{{}^0V} {}^0\rho_s\, g\, \delta u_3\, dV + \int_{{}^0S_B} \rho_w g^0 x_3^0 n_i\, \delta u_i\, dS. \tag{3}$$

If we linearize Eq. (2) at the static equilibrium state, and subtract Eq. (3) from the linearized Eq. (2), we obtain the steady state equation (Kim et al., 2013)

$$-\omega^2 \int_{{}^0V} {}^0\rho_s u_i\, \delta u_i\, dV + \int_{{}^0V} C_{ijkl}\, e_{kl}\, \delta e_{ij}\, dV - \int_{{}^0S_B} \rho_w g\, u_3\, {}^0n_i\, \delta u_i\, dS$$
$$= -\int_{{}^0S_B} p_d\, {}^0n_i\, \delta u_i dS, \tag{4}$$

where C_{ijkl} is the stress–strain relation tensor (k and l vary from 1 to 3), and

$${}^tu_i = {}^tx_i - {}^0x_i = \mathrm{Re}\{u_i e^{j\omega t}\},\ {}^te_{ij} = \mathrm{Re}\{e_{ij} e^{j\omega t}\},\ {}^tp_d = \mathrm{Re}\{p_d e^{j\omega t}\} \tag{5}$$