Applied Ocean Research 30 (2008) 287–296

Contents lists available at ScienceDirect

Applied Ocean Research

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

Hydroelastic analysis of pontoon-type circular VLFS with an attached submerged plate

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ARTICLE INFO

Article history:
Received 20 August 2008
Received in revised form
3 December 2008
Accepted 13 December 2008
Available online 28 January 2009

Keywords:
Circular plate
Submerged horizontal plate
Anti-motion device
Hydroelastic analysis
Very large floating structures
Mindlin plate theory

ABSTRACT

This paper is concerned with the hydroelastic analysis of a pontoon-type, circular, very large floating structure (VLFS) with a horizontal submerged annular plate attached around its perimeter. The coupled fluid–structure interaction problem may be solved by using the modal expansion method in the frequency domain. It involves, firstly, the decomposition of the deflection of a circular Mindlin plate with free edges into vibration modes that are obtained analytically. Then the hydrodynamic diffraction and radiation forces are evaluated by using the eigenfunction expansion matching method which can also be done in an exact manner. The hydroelastic equation of motion is solved by the Rayleigh–Ritz method for the modal amplitudes, and then the modal responses are summed up to obtain the total response. The effectiveness of the attached submerged annular plate in reducing the motion of VLFS has been confirmed by the analysis.

1. Introduction

For a mat-like VLFS (Very Large Floating Structure) the structural length to the characteristic length (which is a function of the flexural rigidity to the buoyancy force) ratio as well as the structural length to wavelength ratio must both be greater than unity [1]. These two ratios imply a flexible large structure where the elastic deformations due to wave action dominate the rigid body motions. Experiments and analyses (see e.g. Wu et al. [2] and Takagi et al. [3]) have shown that the amplitude of the vertical deflection at the edges is larger than those in the interior of the VLFS, thereby confirming that the floating structure undergoes elastic deformation.

There are some ways to reduce the wave forces on the VLFS. The traditional way is by using breakwaters that reduce the height of the incident water waves impacting the leeward side to an acceptable level. However, in many cases such as for consideration of environmental protection and economics in open sea, breakwaters with high wave transmission are adopted and the response at the ends of VLFS may become an obstacle to the facilities mounted on the floating structures. Recently, anti-motion devices have been proposed as alternatives for reducing the effect of waves on the VLFS where the wave dissipation effect of breakwaters is small or there are no breakwaters. An anti-motion device is a body attached to an edge of the VLFS so it does not need a mooring system like floating breakwaters and the time needed for construction is also shorter.

Ohkusu and Nanba [4] proposed an approach that treats the motion of the VLFS as a propagation of waves beneath a thin elastic-platform. According to this approach, the motion of the VLFS is presented as waves. That means the anti-motion coincides with a reduction of wave-transmission from the outside to the inside of the VLFS. Following this idea, some simple anti-motion devices have been proposed and investigated. Takagi et al. [5] proposed a box-shaped anti-motion device and investigated its performance both theoretically and experimentally. They found that this device reduces not only the deformation but also the shearing force and moment of the platform. The motion of the VLFS with this device is reduced in both beam-sea and oblique sea conditions.

A horizontal single plate attached to the fore-end of the VLFS was proposed and investigated experimentally by Ohta et al. [6]. The experimental results showed that the displacement of the VLFS with this anti-motion device is reduced significantly at the edges and in the inner parts as well. They suggested that it would be possible to eliminate the construction of breakwaters in a bay where waves are comparatively small. Utsunomiya et al. [7] made an attempt to reproduce these experimental results by numerical analyses. The comparison of the numerical results with

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doi:10.1016/j.apor.2008.12.002

the experimental results showed that their simple model can reproduce the reduction effect only qualitatively. A more precise model considering rigorously the configuration of the submerged horizontal plate within the framework of linear potential theory is constructed in a study by Watanabe et al. [8] and they validated their model with experimental results.

The foregoing investigations have shown the effectiveness of the horizontal single plate anti-motion device in reducing the motion of a rectangular VLFS under the action of waves. In practice, a VLFS can take on any shape. Watanabe et al. [9] reviewed the various shapes of VLFS that have been treated by researchers. The hydroelastic response of a circular floating thin plate has been studied by some researchers such as Hamamoto and Tanaka [10], Hamamoto [11], Zilman and Miloh [12], Tsubogo [13,14], and Peter et al. [15]. These studies adopted the classical thin plate theory that neglects the effects of transverse shear deformation and rotary inertia on the plate deformation. Recently Watanabe et al. [16] studied the hydroelastic response of a circular VLFS with allowance for these aforementioned effects. Their analytical results serve as benchmark solutions for the verification of numerical techniques and software for hydroelastic analysis.

In this paper, we investigate the effectiveness of a horizontal annular plate anti-motion device in reducing vertical deflections as well as stress-resultants of a circular VLFS under wave action. In earlier studies on this device attached to the fore-end of a rectangular VLFS, the vertical displacement at the back-end is noted to be still relatively large. Therefore, we will analyze a circular VLFS with this device attached completely around its edge. We formulate the diffraction and radiation potentials using the eigen-function expansion method which was originally proposed by Stoker [17] for the estimation of the elastic floating breakwater. This method has been widely applied in many studies such as the study of elastic deformation of ice floes (e.g., Evans and Davies [18], Fox and Squire [19], Meylan and Squire [20]) and study of the oblique incidence of surface waves onto an infinitely long platform (e.g., Sturova [21], Kim and Ertekin [22]). Takagi et al. [5] and Watanabe et al. [8] also applied this method to analyze the box-shaped and single plate anti-motion device to a rectangular VLFS. We will compare obtained results of a VLFS with a single plate anti-motion device with the results of the VLFS alone to show the efficiency of this device for reducing the vertical deflections and stress-resultants.

2. Basic assumptions, equations and boundary conditions for circular VLFS

The fluid-structure system and the cylindrical coordinates system are shown in Fig. 1. The origin of the coordinates system is placed on the flat sea-bed and the z-axis is pointing upwards. The undisturbed free surface is on the plane $z = H$, and the sea-bed is assumed to be flat at $z = 0$. The floating, flat, circular plate has a radius of R and a uniform thickness h. A zero draft is assumed in simplifying the fluid-domain analysis. The horizontal annular plate of width $2a$ is attached at the perimeter of the circular VLFS at a submerged level $z = d$. A sinusoidal plane wave is assumed to be incident to the VLFS at $\theta = 0$. The problem at hand is to determine the effectiveness of the submerged horizontal plate in reducing the deflections and stress-resultants of the uniform circular plate under the wave action. Below, the governing equations and boundary conditions for the hydroelastic analysis are presented. The hydroelastic analysis is performed in the frequency domain.

Considering time-harmonic motions with the complex time dependence $e^{i\varpi t}$ being applied to all first-order oscillatory quantities, where i represents the imaginary unit, ϖ the angular frequency of the wave and t the time, the complex velocity potential $\phi(r, \theta, z)$ is governed by the Laplace's equation:

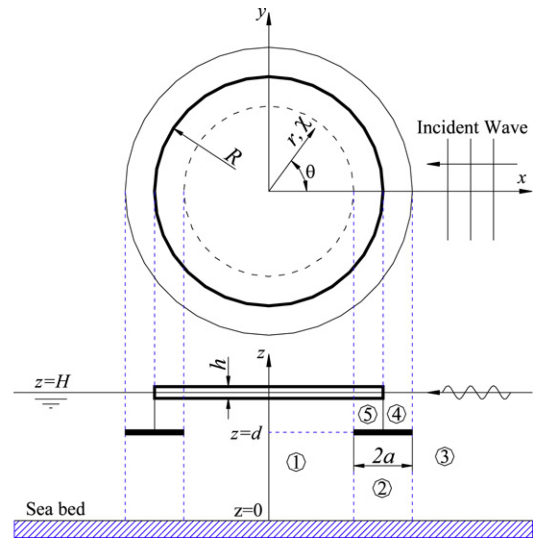

Fig. 1. Geometry of uniform circular VLFS with submerged plate and coordinate system.

$$\nabla^2\phi(r, \theta, z) = 0 \tag{1}$$

in the fluid domain. The potential must satisfy the following boundary conditions on the free surface, on the sea-bed, on the wetted bottom surface of the floating body and on the submerged horizontal annular plate:

$$\frac{\partial\phi(r,\theta,z)}{\partial z} = \frac{\varpi^2}{g}\phi(r,\theta,z) \quad \text{on } z = H, \quad r > R \tag{2}$$

$$\frac{\partial\phi(r,\theta,z)}{\partial z} = 0 \quad \text{on } z = 0 \tag{3}$$

$$\frac{\partial\phi(r,\theta,z)}{\partial z} = \mathrm{i}\varpi w(r,\theta) \quad \text{on } z = H, \quad r \le R \tag{4}$$

$$\frac{\partial\phi(r,\theta,z)}{\partial z} = \mathrm{i}\varpi w(R,\theta) \quad \text{on } z = d, \quad R - a \le r \le R + a \tag{5}$$

where $w(r, \theta)$ is the vertical complex displacement of the VLFS, and g the gravitational acceleration.

The radiation condition for the scattering and radiation potential is also applied at infinity.

$$\lim_{r\to\infty} \sqrt{r}\left[\frac{\partial(\phi-\phi_I)}{\partial r} + \mathrm{i}k(\phi-\phi_I)\right] = 0 \quad \text{as } r \to \infty \tag{6}$$

where r is the radial coordinate measured from the center of the circular VLFS, k the wave number, and ϕ_I the potential representing the undisturbed incident wave:

$$\phi_I = \frac{\mathrm{i}gA\cosh kz}{\varpi\cosh kH}e^{\mathrm{i}kx} = \frac{\mathrm{i}gAM_0^{1/2}}{\varpi\cosh kH}Z_0(z)\sum_{n=0}^{\infty}\varepsilon_n i^n J_n(kr)\cos n\theta \tag{7}$$

where $\varepsilon_0 = 1$, $\varepsilon_n = 2\ (n \ge 1)$; A the amplitude of the incident wave; J_n the Bessel function of the first kind of order n; and

$$k\tanh kH = \frac{\varpi^2}{g} \tag{8}$$

$$Z_0(z) = M_0^{-1/2}\cosh kz \tag{9}$$

$$M_0 = \frac{1}{2}\left(1 + \frac{\sinh 2kH}{2kH}\right). \tag{10}$$

By assuming the circular VLFS to be an elastic, isotropic, shear deformable plate, the motion of the floating body is governed by