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ScienceDirect
Ocean Engineering 34 (2007) 696–708
OCEAN ENGINEERING
www.elsevier.com/locate/oceaneng

Hydroelastic responses and drift forces of a very-long floating structure equipped with a pin-connected oscillating-water-column breakwater system

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Received 27 December 2005; accepted 30 May 2006
Available online 25 September 2006

Abstract

The hydroelastic responses of a very-long floating structure (VLFS) in waves connected to a floating oscillating-water-column (OWC) breakwater system by a pin are analyzed by making use of the modal expansion method in two dimensions. The Bernoulli–Euler beam equation for the VLFS is coupled with the equations of motions of the breakwater taking account of the geometric and dynamic boundary conditions at the pin. The Legendre polynomials are employed as admissible functions representing the assumed modes of the VLFS with pinned-free-boundary conditions. It has been shown numerically that the deflections, bending moments and shear forces of the VLFS in waves can be reduced significantly by a pin-connected OWC breakwater. The time-mean horizontal drift forces of the VLFS equipped with the breakwater calculated by the near-field method are also presented.

Keywords: VLFS; Hydroelastic responses; Pinned-free-boundary conditions of a floating Bernoulli–Euler beam; Pin-connected floating breakwater; Drift force; Relative motions; OWC

1. Introduction

In order to reduce the hydroelastic responses of a very-long floating structure (VLFS) in waves, a box-shaped anti-motion device rigidly attached to the weather-side edge of a VLFS has been proposed by Takagi et al. (2000). The anti-wave performance of a submerged horizontal plate attached to the weather-side end of a VLFS has been studied experimentally by Ohta et al. (1999) and analyzed by Watanabe et al. (2003). The hydroelastic response reduction performance of a oscillating-water-column (OWC) breakwater system freely floating in front of a VLFS has been presented by Hong et al. (2006) where the boundary-value problem for the velocity potential have been solved by making use of a Green integral equation with Kelvine-type Green function in a finite-depth water. In this paper, the hydroelastic responses of a two-dimensional VLFS connected to the floating-OWC breakwater system, by a pin have been analyzed by making use of the modal expansion method. The two-dimensional VLFS is modeled as a Bernoulli–Euler beam. The relative motions between the flexible VLFS and the rigid floating breakwater have been formulated taking account of the geometric and dynamic boundary conditions at the pin. The Legendre polynomials are employed as admissible functions representing the assumed modes of the VLFS with pinned-free-boundary conditions of the Bernoulli–Euler beam. Numerical results have been presented to show the hydroelastic response reduction performance of the pin-connected OWC breakwater system.

2. Theoretical analyses

A VLFS is freely floating on the free surface of finite-depth water under gravity. Cartesian coordinates (x, y, z)

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0029-8018/$ - see front matter
doi:10.1016/j.oceaneng.2006.05.004

Nomenclature

$\mathbf{D}^{\mathrm{B}}(M)$ displacement vector of a point M on the breakwater
$\mathbf{D}^{\mathrm{V}}(M)$ displacement vector of a point M on the VLFS
E Young's modulus of the VLFS
F_x time-mean horizontal drift force
$F^{\mathrm{B}}{}_k$ wave exciting force coefficients of the breakwater
$F^{\mathrm{C}}{}_k$ excitation coefficients of the breakwater due to the air pressure in the OWC chamber
$F^{\mathrm{V}}{}_k$ generalized wave exciting force coefficients of the VLFS
H water depth
$h_l(x)$ $(l = 2, 3, \ldots, N)$ admissible functions
I moment of inertia of the VLFS
K_{kl} stiffness matrix of the VLFS
m_0 wave number
$M(x)$ bending moment of the VLFS
$m(x)$ mass distribution of the VLFS
M^{B}_{kl} inertia coefficients of the breakwater
$\mathrm{MB}^{\mathrm{BB}}_{kl}$ hydrodynamic coefficients of the breakwater due to its own motions
$\mathrm{MB}^{\mathrm{BV}}_{kl}$ hydrodynamic coefficients of the breakwater due to the motions of the VLFS
$\mathrm{MB}^{\mathrm{C}}_{kl}$ coefficients of the breakwater due to the air pressure in the OWC chamber
M^{V}_{kl} generalized inertia coefficients of the VLFS
$\mathrm{MB}^{\mathrm{VB}}_{kl}$ hydrodynamic coefficients of the VLFS due to the motion of the breakwater
$\mathrm{MB}^{\mathrm{VV}}_{kl}$ hydrodynamic coefficients of the VLFS due to its own motions
$P_n(\xi)$; $n = l - 2$; $l = 2, 3, 4, \ldots$ Legendre polynomials of order n
q^{B}_l $(l = 1, 2, 3)$ complex amplitude of rigid sway, heave, and roll motions of the breakwater
q^{V}_1 complex amplitude of the rigid sway motion of the VLFS
q^{V}_l $(l = 2, 3, \ldots, N)$ complex amplitude of generalized modes of the VLFS
$\mathbf{Q} = Q_x\mathbf{e}_1 + Q_y\mathbf{e}_2$ reaction force at the pin
$Q(x)$ shear force of the VLFS
$\mathrm{R}^{\mathrm{B}}_{kl}$ hydrostatic restoring coefficients of the breakwater
$\mathrm{R}^{\mathrm{V}}_{kl}$ hydrostatic stiffness matrix of the VLFS
S^{B} wetted surface of the breakwater
S^{V} wetted surface of the VLFS
$S^{\mathrm{B}}_{\mathrm{W}}$ waterplane of the breakwater
$S^{\mathrm{V}}_{\mathrm{W}}$ waterplane of the VLFS
$w(x)$ vertical displacement of the VLFS
$(x_a, 0)$ coordinates of the pin
$(x^{\mathrm{B}}_{\mathrm{o}}, y^{\mathrm{B}}_{\mathrm{o}})$ coordinates of the center of rotation of the breakwater
Ψ_0 incident wave potential
Ψ_{S} scattering wave potential
Ψ_{R} radiation wave potential
ψ^{B}_l $(l = 1, 2, 3)$ unit-amplitude radiation potentials due to the motions of breakwater
ψ^{V}_l $(l = 1, 2, \ldots, N)$ unit-amplitude radiation potentials due to the motions of the VLFS
γ equivalent linear damping parameter

attached to the mean position of the VLFS are employed with the origin at the center of the waterplane, and the x-axis parallel to the lengthwise direction of the VLFS and the y-axis vertically upwards. There are no motions in the direction of z-axis. A floating OWC breakwater system is connected to the left end of the VLFS by a pin as shown in Fig. 1. The breakwater performs simple harmonic rigid-body oscillations of small amplitude about its mean position with circular frequency ω of plane progressive linear waves incident from $x = -\infty$. The displacement of a point $M(x, y)$ of the breakwater can be expressed as follows:

$$\mathbf{D}^{\mathrm{B}}(M) = q^{\mathrm{B}}_1\mathbf{e}_1 + q^{\mathrm{B}}_3\mathbf{e}_3 \times [(x - x^{\mathrm{B}}_{\mathrm{o}})\mathbf{e}_1 + (y - y^{\mathrm{B}}_{\mathrm{o}})\mathbf{e}_2)], \tag{1}$$

where q^{B}_l $(l = 1, 2, 3)$ are the complex amplitude of rigid sway, heave, and roll motions of the breakwater and $(x^{\mathrm{B}}_{\mathrm{o}}, y^{\mathrm{B}}_{\mathrm{o}})$ the coordinates of the center of rotation.

The horizontal motion of the VLFS is assumed to be a rigid sway motion with complex amplitude q^{V}_1. The vertical displacement $w(x)$ of the VLFS can be found by solving the Bernoulli–Euler beam equation

$$(EIw(x)'')''\mathrm{e}^{-i\omega t} = f(x)\,\mathrm{e}^{-i\omega t}, \tag{2}$$

where E is Young's modulus, I the moment of inertia and $f(x)$ the external force field.

According to the Rayleigh–Ritz method, $w(x)$ can be expressed as

$$w(x)\,\mathrm{e}^{-i\omega t} = \sum_{l=2}^{N} (q^{\mathrm{V}}_l \mathrm{e}^{-i\omega t}) h_l(x), \tag{3}$$

where $h_l(x)$ are the admissible functions and q^{V}_l $(l = 2, 3, \ldots, N)$ the corresponding complex amplitude. It should be noted that the pin is moving in accordance with the relative motions between the VLFS and the pin-connected breakwater.

The displacement of a point $M(x, y)$ of the VLFS can be expressed as follows:

$$\mathbf{D}^{\mathrm{V}}(M) = q^{\mathrm{V}}_1\mathbf{e}_1 + w(x)\mathbf{e}_2. \tag{4}$$

The pinned-free-boundary conditions of the VLFS modeled as a Bernoulli–Euler beam are

$$w(x)'' = 0 \quad \text{at} \quad x = -L_{\mathrm{V}}/2, \tag{5}$$