Applied Ocean Research 58 (2016) 37–48

Contents lists available at ScienceDirect

Applied Ocean Research

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

Gravity wave interaction with a flexible circular cage system

S. Mandal, T. Sahoo*

Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology, Kharagpur 721 302, India

ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 12 March 2016
Accepted 13 March 2016
Available online 2 April 2016

Keywords:
Hydroelastic analysis
Circular cage system
Fourier-Bessel series
Small amplitude wave theory
Least squares approximation method

ABSTRACT

The present study deals with the hydroelastic analysis of a floating flexible circular cage system in finite water depth under the assumption of small amplitude waves and structural response. The flexible cage system is modeled as a surface-piercing porous flexible cylinder having a flexible porous membrane type bed which is under the action of uniform tension. Using the Fourier-Bessel series solution and least squares approximation method, the mathematical problem is handled for solution by matching the velocity and pressure at the fluid-structure interfaces. Further, the flexible cage system is assumed to be kept fixed at the free surface and the submerged end. The efficiency of the cage system is studied by analyzing the hydrodynamic force, effect of structural porosity and deflections of the flexible walls and bed of the cage system. The findings of the present study are helpful in the design of various types of floating cage system for marine aquaculture which can withstand the wave loads of varied nature at calm water location in the coastal area.

1. Introduction

During the last five decades, due to rise in human population and the living standard of people around the world, there is an immense growth in mariculture compared to that of land based food production. In addition, the depletion in fish catching from the open sea has put significant pressure on the mariculture production around the globe. As a result, mariculture as a significant food production sector has grown at rates equivalent to about a doubling of production each decade (see [9]). Fish farms are typically located at near shore regions, and their expansions are limited due to hydrodynamics conditions of aquaculture. These conditions are an important determinant of the suitability of a site for fish production, as well as the spatial size and magnitude of the environmental effects. Detail literature review of ecological effects of aquaculture can be found in [7]. Due to an increase in activities in aquaculture, now a days many fishing farms are located in open ocean environment which are more exposed to wave loads due to waves and current. As a result, during the last few decades, several studies have been conducted involving numerical, physical modeling and field measurements of the net cage fish farming system and emphases are given to understand the role of ocean wave and current on the floating cage system for its effective use and design.

Recent interest in large-scale commercial culturing of marine fish in cages has prompted a detailed look at the technical and economic aspects of this emerging industry. The definition of state-of-the-art, design and operating problems are discussed and areas needing technological improvements are identified with detail review of the technology and economics of marine fish cage systems in [13]. To develop an effective cage system, it is important to understand the dynamic wave loads acting on the net structure as a whole as waves pass through the net. Chwang [6] developed a porous wave maker theory to analyze small-amplitude surface waves produced by horizontal displacement oscillations of a porous vertical structure. Chan and Lee [4] investigated the scattering of surface waves by a flexible fishnet modeled as a freely-flexible permeable barrier. Often the vertical part of the cage system is modeled as flexible porous membrane type hollow cylinder. Abul-Azm and Williams [1] presented an approximate method to estimate the hydrodynamic loadings and dynamic responses between flexible cylinders in waves. Huang et al. [12] analyzed the combined effects of waves and uniform current on gravity-type cages using a numerical model. They have shown that the problems regarding volume deformation and mooring tension caused by a wave-current field are more than those caused by a wave flow field. Wu et al. [26] carried out experiments and validated the experimental results with numerical simulations to understand the hydrodynamic behaviors of a double-column floating system of gravity cage under wave actions. Mandal et al. [20] investigated the wave interaction with a net cage system with rigid bottom and observed that wave load on the cage decreases with an increase in cage radius and structural

* Corresponding author. Tel.: +91 3222283792.
E-mail address: tsahoo1967@gmail.com (T. Sahoo).

http://dx.doi.org/10.1016/j.apor.2016.03.005
0141-1187/

porosity. Xu et al. [27] investigated the hydrodynamic behaviors of multiple net cages under the actions of waves and currents and have demonstrated that for a multi-cage system, the maximum tension force on the anchor lines increases with an increase in number of net cages. Li et al. [17] analyzed both experimentally and numerically the wave-induced acceleration of the elastic floater in the floating cage used in fish farming. Recently, Su et al. [23] investigated the hydrodynamic response of a flexible fish net cylinder modeled as a porous, freely-flexible cylinder, that deforms like a one-dimensional beam in regular waves in a finite water depth by using linear wave theory. In most the aforementioned analytical studies, the cage bottom is modeled as rigid. Cho and Kim [5] developed an effective boundary element method to study the interaction of waves with a horizontal porous flexible membrane. From their results, it was found that with a small inclination angle, wave-blocking performance of a porous membrane can be improved. However, in the present study, the emphasis is given on wave interaction with flexible net cage system including bottom effect of the cage for the use of fish farming.

In the present study, surface wave diffraction by a surface-piercing flexible circular cage system is investigated under the assumption of small amplitude water wave theory and structural response, and non-linear effects due to wave-body interactions are not taken into account. The cage structure is modeled as a two-dimensional membrane having fine pores using the membrane equation including the bottom effect of the cage. Cylindrical vertical cage surface is modeled using the one dimensional string equation. Moreover, the cage system is assumed to be fixed at the free surface and the submerged end. Using the Fourier-Bessel series solution and least squares approximation method, the mathematical problem is handled for solution by matching the velocity and pressure at the fluid-structure interface. Convergence study has been done and a table is provided to highlight justification on the number of terms in the infinite series considered in the present study. The efficiency of the cage system is studied by analyzing the hydrodynamic force, effect of structural porosity and deflection of the flexible cage for various wave and structural parameters. Contour plots and mesh plots are drawn to demonstrate the flow around the cage system and also the amplitude of free surface elevation and flexible membrane deflection. The present model is an idealization of a complex cage system and is suitable for installation at calm water locations dominated by short waves in the coastal area. The results obtained using this linear model can be used to obtain the second order wave forces acting on the cage system.

2. Wave interaction with a cylinder system

In this section, surface gravity wave interaction with a porous and flexible cylinder system referred as a net cage system is analyzed under the assumption of small amplitude water wave theory and structural response assuming that the wave past the porous structure obeys Darcy's law. The solution of the associated mathematical problem is obtained using least squares approximation method and characteristics of the Fourier-Bessel series are used to deal with problems in cylindrical co-ordinate system.

2.1. Mathematical formulation

Under the assumption of the linearized theory of water waves and small amplitude structural response, the physical problem is considered in the three dimensional polar coordinate system (r, θ, z) in water of finite depth H. The cage system is assumed to be surface-piercing in nature and is of negligible thickness as in Fig. 1. The cage system consists of a cylindrical porous membrane of radius a and length h having a porous membrane bottom. Both the vertical

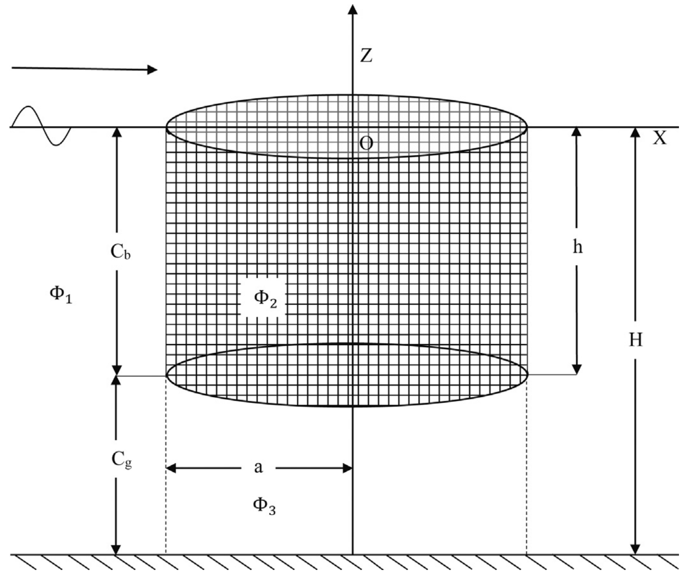

Fig. 1. Schematic diagram of net cage system.

and horizontal sections of the cage are acting under uniform tensions T_v and T_h respectively. The horizontal structure is modeled as a two-dimensional membrane in the cylindrical polar coordinate, whilst the vertical membrane is modeled as a one-dimensional string. The axis of the cylindrical cage system is at $r = 0$, with z axis being vertically upward and the fluid has an undisturbed free surface located at $z = 0$. The fluid occupies the region $0 < r < \infty$, $-H < z < 0$ except the cage system. The notations C_b and C_g represent the submerged and the gap portions of the cage system respectively with $C_b = (-h \le z \le 0)$ and $C_g = (-H \le z \le -h)$. The fluid domain is divided into three regions namely; Region 1: $(-H \le z \le 0, r \ge a)$, Region 2: $(-h \le z \le 0, r \le a)$ and Region 3: $(-H \le z \le -h, r \le a)$. Assuming that the fluid is inviscid and incompressible, and the flow is irrotational and simple harmonic in time with angular frequency ω. Thus, the velocity potentials $\Phi_j(r, \theta, z, t)$ in the respective fluid regions are of the forms $\Phi_j(r, \theta, z, t) = \mathrm{Re}\{\phi_j(r, \theta, z)e^{-i\omega t}\}$, where ϕ_j (for $j = 1, 2, 3$) are the spatial components of the velocity potentials. The velocity potential $\Phi_j(r, \theta, z, t)$ satisfies the three-dimensional Laplace equation which is given by

$$\nabla^2_{r\theta}\Phi_j + \Phi_{jzz} = 0 \quad \text{in the respective fluid domain,} \tag{1}$$

where $\nabla^2_{r\theta} = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}$, along with the linearized free surface boundary condition

$$\frac{\partial^2 \Phi_j}{\partial t^2} + g\frac{\partial \Phi_j}{\partial z} = 0 \quad \text{for} \quad j = 1, 2 \quad \text{on} \quad z = 0, \tag{2}$$

and the bottom boundary condition

$$\frac{\partial \Phi_j}{\partial z} = 0 \quad \text{for} \quad j = 1, 3 \quad \text{on} \quad z = -H, \tag{3}$$

where g is the acceleration due to gravity. Assuming that flexible porous membrane bed of the cage system satisfies Darcy law for flow past a porous structure, the linearized kinematic boundary condition yields (see [5])

$$\frac{\partial \Phi_2}{\partial z} = \frac{\partial \Phi_3}{\partial z} = ik_0 G\{\Phi_3 - \Phi_2\} + \frac{\partial \zeta}{\partial t}, \quad \text{at} \quad z = -h, \tag{4}$$