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Hydrodynamic behaviors of an elastic net structure

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ABSTRACT

Recently, submerged sea cages are utilized in aquaculture industry. It is an important matter how to estimate the mooring force of submerged sea cages because of a harsh sea condition. In this study, to solve the mooring problem of the submerged sea cages, the authors deal with the hydrodynamic behaviors of an elastic net structure as a physical model of a submerged sea cage as a first step of this problem. A cubic shaped elastic net structure was employed to estimate the mooring forces extending the authors' previous study of an elastic plane net and its mooring behavior was estimated. The mooring displacement and mooring tension were calculated and the results are compared with experimental results. From those results, qualitative estimation for the mooring forces and mooring displacements of an elastic net structure are investigated. The mooring behaviors at various nets' pre-tension are also calculated and the result suggests that the sea cage nets' pre-tension affect to its mooring behaviors.

1. Introduction

Recently, with decreasing ocean resources and expanding needs on seafood, the production from marine fishery can hardly meet the demand from the fish markets. Increasingly, attention has been attracted to the aquaculture industry. Traditional aquaculture farms are generally located in sheltered inshore areas. The expansion of the cultured production is limited owing to the environmental problems and lack of availabilities of bay. In addition, the coastal aquaculture has bad influence on not only environment but also cultured fish. In the report by NMF (2011), it is stated that the coastal aquaculture pollutes the sea water around coastal sea cages, and this causes diseases of cultured fishes. Therefore, investors have considered offshore aquaculture, which has various advantages. The offshore aquaculture is a promising system for providing cultured fish with a high productivity and a high quality. As the sea cages are moved to a deep and open sea area, water exchanges become easier. It brings clean sea water that is rich in oxygen into the sea cages. Also, there is less influence on the environment since the settlement of sea lice and fouling organisms are reduced (Svealv, 1988). In addition, large-scale aquaculture is more cost effective (Jensen et al., 2007). However, the offshore sea condition is harsh and sea cages have to survive in various situation. Meanwhile, a new challenge is also confronted. It is an important issue to protect offshore farms from a severe sea state caused by bad weather such as typhoons and hurricanes. In order to reduce the environmental loads from waves, most sea cages are submerged in offshore areas. During the past decade, various types of sea cage installed at exposed sea sites have been developed in the world. The behavior of sea cages in waves has been investigated. For example, large submergible cages, named Sea Station, have been developed by Ocean Spar to avoid the damage caused by a harsh environment. The University of New Hampshire has been involved in a project on open ocean aquaculture (Celikkol et al., 2006). Fredriksson et al. (2006) have studied the heave response of a central spar sea cage (Sea Station). Later, Fredriksson et al. investigated the mooring forces of a single sea cage (Fredriksson et al., 2003a) as well as an array of sea cages (Fredriksson et al., 2003b, 2004). An experimental investigation of the wave forces on net structures has been made by Lader et al. (2007a) and Lader et al. (2007b).

In many cases, sea cages are usually made of net materials. An interesting problem is raised, i.e. how to evaluate the effect on the hydrodynamic loads and its mooring forces in an efficient way. One of possible approaches is to regard the net as a piece of elastic perforated membrane. Some researchers, who are interested in the break water effect of a submerged elastic or rigid perforated plate have investigated this subject. To give some examples, the downstream waves of a submerged rigid perforated plates have been investigated by Yu and Chwang (1994). The submerged membrane with perforated flexibilities has been studied by Cho and Kim (1998) and Cho and Kim (2000). Comparison has also been made between calculation and measurement about wave height in their work. The above-mentioned investigations are all involved with two-dimensional problems.

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In this work, the hydrodynamic behavior of a cubic shaped net structure is investigated by means of linear hydroelastic theory and experimental tests. Each side of the cubic net is regarded as a perforated membrane. The deformation of the net is expressed by an expansion of natural modes, the modal function of which are deduced from the free vibration of a rectangular membrane. The formulated diffraction and radiation problem are solved by means of the hybrid method composed of eigenfunction expansion method in the outer region and boundary element method in the inner region. The modal amplitudes of deformation are solved from the motion equation and their effects on the hydrodynamic forces are examined. This assumption may not present the deformation properties of actual sea cage, but the present work will be the first step to solve the problem. This approach is the extension of the authors' previous work (Bao and Kinoshita, 2009; Ito et al., 2012).

In addition to diffraction and radiation problem, the mooring forces of a cubic net are investigated. In mooring problem, the cubic net is moored in regular waves. The mooring displacements and mooring forces are estimated by solving the motion equation of moored cubic net, using the estimated hydrodynamic forces.

The hydrodynamic forces depend on nets' pre-tension, and consequently variation of the mooring forces and displacements are affected. If the pre-tension reaches above a certain magnitude, the elastic nets' hydrodynamic forces are close to the values of rigid nets. However, if the pre-tension is low and near zero, the elastic nets' hydrodynamic forces are totally different from those of rigid nets.

Experimental tests are also carried out to validate the estimated results. The authors arranged one test model composed of metallic frame and elastic cord, and it is moored by four wires in a wave basin. The mooring tensions and mooring displacements are measured in the tests, and these are compared to the estimated values.

The authors analyzed the mooring behavior of an elastic cubic net on the most basic condition, i.e. the deformation of the net is assumed to be small and linear, to take in the effect of elasticity. It is true that the most of actual sea cages' deformation are large and beyond the range of linear deformation due to small pre-tension, and thus the present results are not directly applicable to them, but the results may contribute to the non-linear analysis of actual sea cages' mooring behavior in the future work as a basic reference.

The boundary value problem is formulated in Section 2. The modal functions to express the net deformation are deduced in Section 3, and the approaches to solve the boundary value problem are discussed in Section 4. The motion equation and hydrodynamic forces are discussed in Section 5. The experimental arrangement is presented in Section 6 including the discussion on the mooring motion equation. The calculated and measured results are compared in Section 7. The mooring forces under the condition of different nets' pre-tension are discussed in Section 7.2. A brief conclusion is given at the end of the paper.

2. Formulation of the problem

In a water of constant depth h, a cubic net is installed. The cubic net's side length is a and its top surface is located at a distance d beneath the water surface. A Cartesian frame (x, y, z) is employed in inner region, and a cylindrical coordinate system (r, θ, z) is adopted to outer region of the present hybrid method. The $x-y$ plane, or equivalently $r-\theta$ plane, coincides with the still water surface and the z axis goes through the center of the top net surface and points upwards (Fig. 1). The division of regions is defined in Section 4.

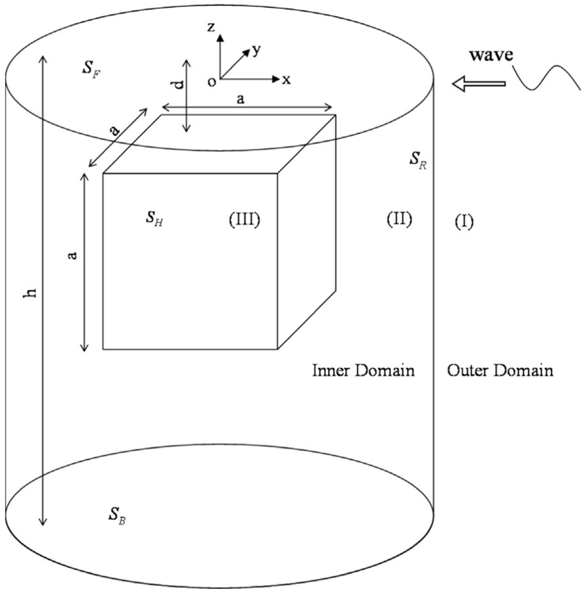

Fig. 1. Definition of coordinate and parameters.

The cubic net, each of its surfaces is tightened with a uniform tension T, is fixed in a train of regular incident waves or forced to make a heaving oscillation about its top surface's average position $z=-d$. The frequency of incident waves or forced heaving oscillation is denoted as ω. The interaction of the cubic net with the ambient wave field is considered within the scope of the linear hydroelastic theory. This means that each surface of the cubic net is treated as an elastic perforated membrane, the deformation of which is represented by a set of natural modes given by

$$\zeta(\mathbf{x};t)=\mathrm{Re}\left[\exp(-\mathrm{i}\omega t)\sum_{m}\sum_{n}\zeta_{mn}W_{mn}(\mathbf{x})\right] \tag{1}$$

where ζ_{mn} represents the unknown complex modal amplitude corresponding to mnth mode. The deformation is assumed to be small so that the displacement can be considered in each surface's normal direction. The definition of the modal function $W_{mn}(\mathbf{x})$, together with the range of the indices m and n, will be given in the next section.

As the fluid motion is considered, under the assumption that the fluid is inviscid and the flow is irrotational, there exists a velocity potential $\phi(\mathbf{x},t)$, which may be decomposed into the form:

$$\phi(\mathbf{x},t)=\mathrm{Re}\left\{\left[\frac{gA}{\mathrm{i}\omega}\phi_D(\mathbf{x})-\mathrm{i}\omega\eta_H\phi_H(\mathbf{x})-\mathrm{i}\omega\sum_{m}\sum_{n}\zeta_{mn}\phi_{mn}(\mathbf{x})\right]\exp(-\mathrm{i}\omega t)\right\}. \tag{2}$$

In Eq. (2), the amplitude of the incident wave is denoted by A while the heaving amplitude is represented by η_H. g is the acceleration due to gravity. The diffraction potential ϕ_D consists of the incident wave potential ϕ_I and the scattering potential ϕ_S, i.e. $\phi_D=\phi_I+\phi_S$. The incident wave potential ϕ_I is well known. For convenience in later use, its expression and the Fourier–Bessel expansion are recorded here as

$$\begin{aligned}\phi_I(x)&=\frac{\cosh\left[k_0(z+h)\right]}{\cosh(k_0h)}\exp\left[k_0(x\cos\beta+y\sin\beta)\right]\\&=\frac{\cosh\left[k_0(z+h)\right]}{\cosh(k_0h)}\sum_{n=0}^{\infty}\epsilon_n\mathrm{i}^nJ_n(k_0r)\cos[n(\theta-\beta)],\\\epsilon_n&=\begin{cases}1 & (n=0)\\2 & (n>0)\end{cases}\end{aligned} \tag{3}$$

where β is the incident wave angle.