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Dynamic responses of floating fish cage in waves and current

Li Li, Shixiao Fu*, Yuwang Xu, Jungao Wang, Jianmin Yang

State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, China

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ABSTRACT

This paper studies dynamic responses of the semi-immerged floater and the fish cage system consisting of the floater and nets in waves and currents. The net and floater is modeled by truss and beam element respectively, where the corresponding geometry nonlinearity in the deformations and motions is considered. A "Buoyancy Distribution" method is developed to address the instantaneous buoyancy on the floater in waves. Particularly, the motions of the flexible floater and the net volume reduction in different wave and current conditions are investigated. The effects of the interactions between the net and floater on the dynamics of the system are also studied. Additionally, the effects of the net drag forces on the dynamic responses of the fish cage system are investigated.

1. Introduction

As the near-shore spaces of today can hardly satisfy the increasing demand for marine foods, the fish farming industry has the tendency to move to offshore area (Lader and Fredheim, 2001; Lee et al., 2009). New challenges may appear due to the severe sea loads when the fish cages move to the more exposed ocean areas.

Large floating structures, such as ships and platforms, are usually treated as rigid bodies, and the wave-induced forces are normally calculated by Green function method based on the potential flow theory. However, regarding small scale floating structures, the viscous nonlinear forces become dominated, and hence the potential flow theory is no longer applicable. Such a condition makes it difficult to predict the dynamic responses of a flexible aquaculture structure in waves and currents.

Many researchers have conducted both experimental and numerical studies on the dynamic responses of the fish cage system. By dividing the net into super elements, Lader and Fredheim (2006) developed a numerical model to study the net deformation in different conditions. A mass-spring model was developed by Lee et al. (2009) to investigate the dynamic behavior of the fish cages. Lader et al. (2007) experimentally investigated the wave forces on the nets by model test. Kristiansen and Faltinsen (2009) studied the nonlinear wave-induced motions of cylindrical-shaped floaters by both model tests and numerical wave tank. Berstad et al. (2005) compared the results by the numerical program Aquasim with the Norwegian Standard 9415. Lader et al. (2008) studied current-induced net deformations by full-scale measurements at sea.

In this paper, dynamic responses of the individual semi-immerged floater and the whole fish cage system including the floater and nets in waves and currents are studied. The net and floater is modeled by truss and beam element respectively. A "Buoyancy Distribution" method is developed to simulate the instantaneous buoyancy on the partly-immerged floater in waves. The motions of the flexible floater and the net volume reduction in different wave and current conditions are investigated. Also studied are the interactions between the net and floater. In addition, by varying the drag coefficient Cd on the nets, we investigate the effect of the net drag forces on the dynamic responses of the whole system.

2. Basic theory

For the floater and the whole fish cage system, the structural dynamic equilibrium equation can be written as:

$$[m][\ddot{x}] + [c][\dot{x}] + [k][x] = G + f_b + f_w + f_c \tag{1}$$

where $[m]$ is the total mass matrix of the floater and nets, $[c]$ is damping matrix from the structural deformations of the floater and nets, $[k]$ is the stiffness matrix of the deformed floater and nets. The loads applied on the structure include gravity G, buoyancy f_b, wave forces f_w and current forces f_c.

The gravity force, as G presents, should be balanced by the static buoyancy force and applied to the system in the first place, before the dynamic analysis, to find out the mean water line of the floating system.

* Corresponding author. Tel.: +86 13501947087; fax: +86 21 34207050x2031.
E-mail address: shixiao.fu@sjtu.edu.cn (S. Fu).

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2.1. Hydrodynamic forces

In traditional linear analysis procedures for large floating structures, buoyancy f_b, wave forces f_w and current forces f_c in Eq. (1) are usually linearly superposed: the buoyancy f_b is represented by the hydrostatic matrix; wave forces f_w are calculated by diffraction and radiation theory; and current forces f_c are calculated by the Morison equations. Instead of diffraction and radiation theory, here Morison equations (Faltinsen, 1990) are used to calculate all of the hydrodynamic forces on the floating fish cage system, including wave forces f_w and current forces f_c. All of the nonlinear interactions between those forces will be represented by hydrodynamic coefficients, the relative motion velocity and acceleration, as shown in the following equations.

$$F = C_m \rho \frac{\pi}{4} D^2 \dot{u} + C_d \frac{1}{2} \rho D |u+U|(u+U) \tag{2}$$

taking the relative motions between the structure and water particle into consideration, the above equation can be further modified as:

$$F = C_m \rho \frac{\pi}{4} D^2 (\dot{u} \pm a_p) + C_d \frac{1}{2} \rho D |u \pm v_p \pm U|(u \pm v_p \pm U) \tag{3}$$

where C_m is inertia coefficient, C_d is drag coefficient, D is cylinder diameter, u is wave velocity, U is current velocity, ρ is water density, the velocity and acceleration of the structure element is v_p and a_p respectively.

2.2. Buoyancy

As Eqs. (2) and (3) present, the buoyancy force is neglected when only Morison equations serve to calculate the external loads on floating system. However, buoyancy remarkably affects the instantaneous hydrodynamic forces on the floating system and should be regarded as one of the external force components.

The buoyancy force on the instantaneous wetted surface of the floater can be written as

$$f_b = \rho g V_m \tag{4}$$

where ρ is water density, V_m is the instantaneous immerged volume of the structure.

In standard FEM analysis software, beam element are usually adopted to simulate the deformations and motions of the floater in current and waves, where the beam section is treated as a 2D point. Whether to take into account the buoyancy in loads depends on the instantaneous position of the beam section point relative to the free surface of waves. Specifically, were the beam section point under the water surface, the buoyancy of the whole cross section would be applied; otherwise, the buoyancy is neglected. However, in real conditions, the partly-immerged floater section leads to time-varying buoyancy. Besides, such buoyancy forces of the submerged portion support the whole cage system. Therefore, the instantaneous buoyancy plays pivotal role in studying dynamic motions and deformations of the floater in waves and current.

Regarding the instantaneous wetted surface effects on the buoyancy forces of the floater, a "Buoyancy Distribution" method is developed by dividing the whole beam section of the floater into several distributed and coupled beams sections as shown in Fig. 1.

Fig. 1 indicates that several separated beam sections are bounded together to simulate the whole original floater cross section. Thus, the instantaneous buoyancy forces of the whole floater section $f_{B\_section}$ should be the sum of the buoyancy on each immerged beam section $(f_{B\_immerged\_beams})_i$, and can be expressed as:

$$f_{B\_section} = \sum (f_{B\_immerged\_beams})_i \tag{5}$$

To insure that the distributed beam section can move and deform as "one section", the following constrain equations are applied to the separated beam section points

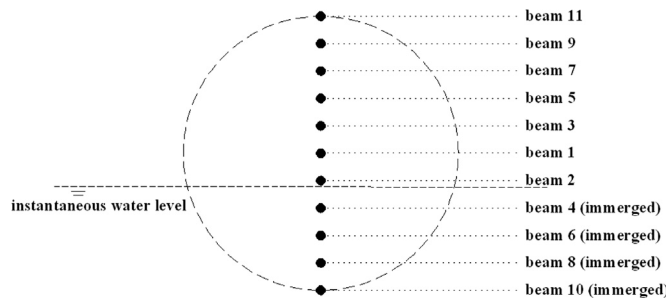

Fig. 1. Illustration of the distributed coupled beam section.

$$u_i^m - u_i^n = 0 \tag{6}$$

where u_i^m and u_i^n represent the ith degree of the freedom (DOF) displacement at beam section point m and n (Dassault System, 2010), which indicates that in addition to the equilibrium of the dynamic motion equations of the whole system, u_i^m are always forced to equal with u_i^n at any moment. By repeatedly applying the constrain equations like Eq. (6), one can assign a same displacement, in the corresponding DOF, to all of the beam section points at a floater section.

Furthermore, to make sure that the distributed beam sections have the same inertia and deforming properties as the original floater, the mass and bending stiffness of the floater should be evenly distributed to separated beams, e.g.

$$m_{section} = \sum m_i \tag{7}$$

$$(EI)_{section} = \sum (EI)_i \tag{8}$$

where $m_{section}$ and $(EI)_{section}$ are the mass density and bending stiffness of the original floater section; m_i and $(EI)_i$ are the mass density and the bending stiffness of the ith beam in the distributed beam section.

3. Numerical examples

3.1. Floater model

Fig. 2 shows the numerical model of the floater, and the main properties of a single floater model are listed in Table1. The floater is modeled by coupled distributed beams, and the nonlinear springs simulate the mooring lines on the floating fish cage system. A zero force is defined when the springs are under compression. The gravity and buoyancy of the floater are balanced to keep the floater exactly half-submerged.

With Eqs. (5)–(8), the section properties of each distributed beams are calculated and then listed in Table 2 where H represents the relative distance from the center of each distributed beam section to the center of the whole floater section, R and I respectively symbolize the radius and inertia moment of each distributed beam section. The density and elastic modules of each beam are set as 512 kg/m^3 and 7044.139 MPa respectively. With the combination of those distributed beams, the bending stiffness of 0.296842 N m^2 and mass density 355 kg/m of the floater cross section properties can be modeled.

3.2. Fish cage model with nets and floater

Fig. 3 shows the numerical model of the fish cage system. The properties of fish cage system, including the floater, nets and the sinker, are listed in Table 3. The distributed beam sections and truss elements without bending stiffness model the floater and the nets separately. At the bottom, we neglect the nets and simulate