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A numerical analysis on the hydrodynamic characteristics of net cages using coupled fluid–structure interaction model

Chun-Wei Bi[a], Yun-Peng Zhao[a,*], Guo-Hai Dong[a], Yan-Na Zheng[b], Fu-Kun Gui[c]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China
[b] School of Ocean and Civil Engineering, Dalian Ocean University, Dalian 116023, China
[c] Marine Science and Technology School, Zhejiang Ocean University, Zhoushan 316000, China

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ABSTRACT

A numerical approach is proposed to simulate the hydrodynamic characteristics of a net cage in a steady current. The numerical approach is based on the joint use of the porous-media fluid model and the lumped-mass mechanical model. The deformation of a net cage can be calculated using the lumped-mass mechanical model and the flow field around a fishing net can be simulated using the porous-media fluid model. Using an appropriate iterative scheme, the coupled fluid–structure interaction between the flow and net cage can be solved, and the steady flow field inside and around a net cage can be obtained. Using the proposed numerical approach, numerical simulations of flow through a single net cage in different currents, single net cage with different weight modes and multiple net cages are investigated. Validation of the numerical model is conducted by comparing the numerical results with the corresponding physical model measurements. The comparisons demonstrate that both the configuration of the net chamber and the flow-velocity results are in accordance with those of the corresponding physical model tests. It was determined that more accurate results can be obtained by considering the coupled fluid–structure interaction between the flow and the net cage.

1. Introduction

The role of aquaculture in food production, economic development and food security is now well recognized. In the aquaculture industry, net cages are becoming prevalent around the world. The environmental conditions inside and around a net cage are important for the welfare and development of the fish. It is now generally accepted that water motion helps to maintain the water quality in a net cage and that sufficient water exchange is critical for efficient and sustainable aquaculture production. However, water motion that is too intense can cause serious deformation of the fishing net and can sharply reduce the effective volume of the net cage (Tsukrov et al., 2003; Fredheim, 2005; Zhao et al., 2007a, 2009; DeCew et al., 2010), which negatively impacts the welfare of the fish. Numerous studies have demonstrated that the force on a net cage is proportional to the square of the flow velocity. Thus, there are small differences in flow velocity that can lead to large differences in force, and in investigations of the forces acting on a net cage, the flow velocity distribution around the net cage usually cannot be ignored. Furthermore, the flow-field characteristics determine the distribution of nutrients, waste and dissolved oxygen in the net cage. Thus, investigation of the flow field inside and around a net cage has become important.

A number of studies have been focused mainly on the flow-velocity reduction downstream from a plane net (Gui et al., 2006; Lee et al., 2008; Patursson et al., 2010; Zhao et al., 2013a), and these investigations form a foundation for studying the flow field within and around net cages. To better understand the hydrodynamic fields of a net cage, extensive investigations have been carried out in recent decades. Aarsnes et al. (1990) conducted a series of experiments to determine the velocity distribution within net-cage systems, and flow velocity-reduction formulae for net cages were developed. Fredriksson (2001) studied the flow velocity in an open-ocean cage with field measurements, and a reduction of approximately 10% was found. Lader et al. (2003) performed a series of experiments to investigate the forces and geometry of a net cage in uniform flow, and an average of 20% velocity reduction was measured inside the cage. Fredheim (2005) calculated the flow distribution around a three-dimensional net structure as a superposition of effects due to individual cylinders (twine) and spheres (knots) and described the wake by a distribution of sources. Li et al. (2005) analyzed the shadowing effect of six practical gravity-cage models by physical model tests, and the flow-reduction coefficients within and downstream of the net cages were obtained. Johansson et al. (2007) performed field measurements at four farms in Norway, and a major reduction was measured in the

* Corresponding author. Tel.: +86 0411 84708950; fax: +86 0411 84708526.
E-mail addresses: Ypzhao@dlut.edu.cn, zhaoyp18@hotmail.com (Y.-P. Zhao).

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current passing through the cages. The measured current reduction was between 33% and 64%. Harendza et al. (2008) conducted experiments in a towing tank with particle image velocimetry (PIV) configurations to investigate the flow velocity distribution around cylindrical fish cages with varying inclination angle and porosity; however, they did not report the flow velocity distribution inside the net cage. Gansel et al. (2011) conducted laboratory tests and field measurements to study the effects of biofouling and fish behavior on the flow field inside and around stocked salmon cages.

However, the efforts mentioned above are mainly concentrated on physical model tests and field measurements. Among the numerical works, Shim et al. (2009) presented a numerical model to simulate the flow field around a net cage with different porosities by treating the net structure as a porous-jump boundary but did not consider net deformation. Zhao et al. (2013b) proposed a three-dimensional numerical model using a porous-media fluid model and presented the flow field inside and around a single net cage and multiple net cages without net deformation. The above review of the literature demonstrates that although some numerical studies have been developed and much progress has been made, no developed numerical model has focused on the interaction between the flow and a net cage with a flexible net.

As an extension to our previous work of Zhao et al. (2013b), a three-dimensional numerical approach is presented based on the joint use of the porous-media fluid model and the lumped-mass mechanical model. Using an appropriate iterative scheme, the coupled fluid–structure interaction problem can be solved and the steady flow field inside and around a net cage can be obtained with the consideration of net deformation in steady current.

This paper is organized as follows. Section 2 describes the porous-media fluid model, the lumped-mass mechanical model and the joint use of the two numerical models. Section 3 contains the numerical simulations and experimental validations of the interaction between flow and net cages using the proposed numerical approach. Flow through a single net cage in different currents and a single net cage with different weight models as well as multiple net cages are simulated. Section 4 is a discussion of the numerical results. Finally, the conclusions are presented in Section 5.

2. Model descriptions

The numerical approach to simulate the interaction between flow and net cage includes two numerical models: the porous-media fluid model and the lumped-mass mechanical model. The porous-media fluid model can simulate the flow field around a plane net with no deformation, and the lumped-mass mechanical model can simulate the deformation of net chamber in a certain current. The joint use of the above two models is presented to solve the coupled fluid–structure interaction problem. The steady flow field around net cages can be obtained by using an appropriate iterative scheme, as explained later in Section 2.3.

2.1. The porous-media fluid model

The porous-media fluid model is introduced to model the flow field around a plane net (Zhao et al., 2013a,b), and the finite volume method is used to solve the governing equations of the numerical model. In this way, a numerical simulation of the flow field around the plane net can be built.

2.1.1. Governing equations

The realizable k–ε model (Shih et al., 1995) is a turbulence model having extensive applicability. It is likely to provide superior performance for flow involving strong pressure gradients. For flow through and around a plane net, strong pressure gradients exist because of the shielding effect of the fishing net. Therefore, the realizable k–ε turbulence model was chosen to solve this problem.

The governing equations describing the realizable k–ε turbulence model are as follows (in tensor form):

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j}(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + S_i \tag{2}$$

where t is time; μ and ρ are the viscosity and the density of the fluid, respectively; μ_t is the eddy viscosity; $P = p + (2/3)\rho k$, where p is pressure; k is the turbulent kinetic energy; u_i and u_j are the average velocity component, respectively; g_i is the acceleration due to gravity; $i, j = 1, 2, 3$ (x, y, z); and S_i is the source term for the momentum equation. More detailed description of the source term is presented in Section 2.1.2.

k equation:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial xj}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{3}$$

ε equation:

$$\frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial xj}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \tag{4}$$

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right], \quad \eta = S\frac{k}{\varepsilon}, \quad S = \sqrt{2S_{ij}S_{ij}}, \quad S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{5}$$

where G_k is the turbulent kinetic energy generated by the average velocity gradient. G_b and Y_M due to buoyancy and compressibility are not necessary when modeling incompressible fluid with no temperature fluctuations, hence $G_b = 0$ and $Y_M = 0$. C_2, $C_{1\varepsilon}$ and $C_{3\varepsilon}$ are constants; S is the modulus of the mean rate-of-strain tensor; σ_k and σ_ε are the turbulent Prandtl number; and S_k and S_ε are source terms that can be defined by the user. The model constants for the realizable k–ε turbulence model are $C_{1\varepsilon} = 1.44$, $C_2 = 1.9$, $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.2$ (Shih et al., 1995).

2.1.2. Porous media resistance coefficients

The porous-media fluid model is a hypothetical model which acts the same water-blocking effect as the fish net by setting the coefficients of the hypothetical porous media. For flow through porous media, a pressure gradient exists:

$$\nabla p = a\vec{u} + b|\vec{u}|\vec{u} \tag{6}$$

where a and b are constant coefficients and $\vec{u}$ is the flow velocity. This expression was proposed by Forchheimer in 1901 based on the Darcy law. For large porosity (e.g., an array of fixed cylinders), turbulence will occur and the quadratic term for the frictional force will completely dominate over the viscous term (the linear term) (Burcharth and Andersen, 1995). In this case, the linear term is only a fitting term, which has no physical meaning and thus it can be negligible.