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Experimental analysis of the hydrodynamic coefficients of net panels in current

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ABSTRACT

The hydrodynamic loads on net panels were affected significantly by the net configuration and the Reynolds number. Six groups of net panels with different materials, net solidities and knot patterns were experimentally analyzed in this study. The concept of the cruciform element was proposed to calculate the hydrodynamic loads on net panels. The effect of the net solidity, the net material, the knot pattern and the Reynolds number on the hydrodynamic coefficients of net panels in current was comprehensively discussed. A formula, which was suitable for the net panels with high solidity, was proposed to estimate the hydrodynamic coefficients of net panels in current based on the theoretical and experimental analysis of the measurements. The results indicated that the relationship between the Reynolds number and the drag coefficient of the net panel was similar to that for the circular cylinder when the net solidity was low (0.190); with the increase of the net solidity, the influence of the Reynolds number on the drag coefficient of the net panel decreased. In addition, the net-grouping standard was discussed and a correction factor for modifying the drag-coefficient of the equivalent net model was proposed.

1. Introduction

The demand for food (referring to FAO [1]) was expected to increase 70% by 2050 and the marine production would play a key role as a source of food, nutrition, income and livelihoods around the world in the future. For easing the potential food crisis and reducing the overfishing, marine aquacultures have attracted the worldwide attention and the large net cage in offshore area is becoming a globally dominant.

In last decades, comprehensive researches have focused on hydrodynamic characteristics and flow fields around net panels. As a pioneer to investigate the flow passing through a screen which is similar to a net panel, Taylor [2] proposed the relative turbulence-intensity method to analyze the wake of the screen and presented a prediction of the drag coefficient, C_d, as a function of the screen solidity. Fridman and Danilov [3] investigated the drag force on nets in steady current and developed an empirical formula of C_d incorporating the Reynolds number of twine and net solidity in current. Milne [4] analyzed the drag force on both knotted and knotless nets and proposed a formula for calculating the drag force on nets with different knot forms. Løland [5] combined the linear free-wake equations with an eddy viscosity formulation to establish a 'sum of cylinder' model for analyzing the relationship between the drag force and the wake generated by the net. Zhan et al. [6] conducted a series of net panel experiments in a towing tank to investigate the effects of net solidities, incidence angles and mesh patterns on the forces acting on nets, and proposed a new formula for the total normal drag on planar and cylindrical nets. Balash et al. [7] measured the hydrodynamic forces on the net panel in a towing tank and suggested a new formula for C_d, in which the drag coefficients for circular cylinders and spheres were adopted to modify the original prediction.

In addition, several numerical models were applied to simulate net structures in current. Li et al. [8] established a lumped mass model to investigate the deformation and the tension distribution of nets based on Morison equation, and Kristiansen and Faltinsen [9] discussed the viscous hydrodynamic forces on nets through a screen type of force model. For simulating the interaction between nets and current, Bi et al. [10] combined the lumped mass model with the porous media method to calculate the deformation of a net panel in the current, and Yao et al. [11] developed a novel hybrid volume approach, combining the mass-spring model with the finite volume method, to simulate the net cage in current.

In recent years, some researches begun to focus on the effect of biofouling attached at the net cage. Biofouling, the organism accumulation on the surface of net twine, would lead to the increase of drag force on the net cage and restrict the water exchange through the nets [12,13]. Swift et al. [14] investigated the drag forces on the biofouled

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nets both in a tow tank and in the field, and it was found that the increase in the drag coefficient caused by biofouling could be up to 240%. Lader et al. [15] analyzed the effect of the hydroid on the drag force on nets through using the physically hydroids model and showed that the drag force on the net panel increase significantly with the increasing hydroid length. Bi et al. [16] used a numerical approach to analyze the wave attenuation through a square array of 16 net cages with different biofouling levels and showed that the damping effect of the cage array increased with the increasing biofouling level. It was accepted extensively that the biofouling was related with the increase of the drag force; however, for predicting the drag force on biofouled nets, it was necessary to parameterize the effect of the biofouling on the drag force on nets. Recently, Gansel et al. [17] investigated the change in drag forces acting on net panels with different solidities and biofouling levels in a flume tank and proposed a transfer function concept to parameterize the effect of biofouling in terms of an equivalent increase in clean net solidity. However, the solidity of clean single nets used in their study ranged from 0.18 to 0.43, while some biofouled nets approached solidity of 0.8. Thus, the experimental results for the high solidity clean nets ($0.43 < Sn < 0.8$) were required for completing their transfer function.

As a basis of the design of the net cage in offshore area, it is significantly important to calculate hydrodynamic loads on net panels. However, on the one hand, previous researches are primarily focused on the net with low solidity; on the other hand, the net deployed in the offshore area is usually affected by the aquatic organism, and the forces on the bio-fouled net are obviously different from the clean net (i.e. the low-solidity nets). Thus, it is beneficial to conduct the comprehensive analysis on the hydrodynamic coefficients of the bio-fouled net panel (i.e. the high-solidity nets). In this study, a novel concept is proposed to consider the influence of the aquatic organism attached on the net panel. The high-solidity net panels were tested in this study, and the diameter of net twine and the mesh size were varied to consider different degrees of contamination of the aquatic organism. In addition, the effects of the knot pattern, the net material and the Reynolds number on the hydrodynamic loads acting on net panels were analyzed, and a net-grouping standard was developed here. A formula was proposed to calculate the hydrodynamic coefficients of net panels based on the experimental data for the nets with the solidity range of 0.190–0.679.

2. Methods

2.1. Hydrodynamic forces on the net panel

In this study, the net with square mesh is considered, and the net panel is divided into numerous cylindrical cruciform elements for the hydrodynamic analysis as shown in Fig. 1. The net panel is characterized by the solidity ratio, the Reynolds number, the projected area and the incident angle of current. The solidity ratio, *Sn*, is defined as the ratio of the projected area of the net twine to the outline area of the net panel, and *Sn* for the square-mesh net panel is given below:

$$Sn = \frac{d_t(2a-d_t)}{a^2} \tag{1}$$

where d_t is the diameter of net twine and a is the length of each side of square mesh. The Reynolds number is defined as:

$$\mathrm{Re} = \frac{d_t U_\infty}{\upsilon} \tag{2}$$

where U_∞ is the incident flow velocity and υ is the kinematic viscosity.

The purpose of this study is to find accurate dependencies of the hydrodynamic force on the net solidity, the Reynolds number and the net material. Thus the incident angle of the net panel remains 0, which means that the normal direction of the net panel is parallel to the current direction and only drag force acts on the net panel in current. The drag force F_d is described as follow:

$$F_d = 0.5\rho C_d U_\infty^2 A_n \tag{3}$$

where C_d is the drag coefficient; A_n is the projected area of the net panel; ρ is the water density. For each cruciform element, the force F_c on the cruciform element can be divided into two parts: the force F_t on the twine and the force F_k on the knot. The drag force on one cruciform element can be expressed as:

$$F_{cd} = F_{td} + F_{kd} \tag{4}$$

and

$$F_{td} = 0.5\rho C_{td} U_\infty^2 (2a-2Kd_t)d_t \tag{5}$$

$$F_{kd} = 0.5\rho C_{kd} U_\infty^2 (K^2 d_t)d_t \tag{6}$$

where C_{td} and C_{kd} are the drag coefficients for the net twine and the knot, respectively; K is the ratio of the diameter of knot to the diameter of twine, which is 1 for the knotless nylon net and 2.25 for the knotted nylon net. The projected area of the cruciform element A_c is expressed as:

$$A_c = (2a-2Kd_t)\cdot d_t + (K^2 d_t)\cdot d_t = (2a-2Kd_t + K^2 d_t)d_t \tag{7}$$

Considering F_{cd} as a function of the projected area A_c, Eq. (4) can be rewritten as follow:

$$F_{cd} = 0.5\rho(\varepsilon_t C_{td} + \varepsilon_k C_{kd})U_\infty^2 A_c \tag{8}$$

where

$$\varepsilon_t = \frac{2a-2Kd_t}{2a-2Kd_t + K^2 d_t} \text{ and } \varepsilon_k = \frac{K^2 d_t}{2a-2Kd_t + K^2 d_t} \tag{9}$$

The drag force on the net panel is calculated as the sum of the drag force on each cruciform element, as follows:

$$F_d = \sum F_{cd} = 0.5\rho(\varepsilon_t C_{td} + \varepsilon_k C_{kd})U_\infty^2 \sum A_c \tag{10}$$

Thus, the drag coefficient of the net panel is expressed as: