The dynamic characteristic of aquaculture net cage considering flexible twine damaged

Zhongqiang Zheng¹, Rong Wan²,³, Zongyu Chang¹,⁴ and Mingtao Chi¹

¹College of Engineering, Ocean University of China, Qingdao, China
²College of Marine Science, Shanghai Ocean University, Shanghai, China
³National Engineering Research Center for Oceanic Fisheries, Shanghai, China
⁴Key Laboratory Ocean Engineering Lab of Shandong Province, Qingdao, China

E-mail: zqzheng@ouc.edu.cn

Abstract. The aquaculture net cage can provide the living space for fish in larger waves and stronger currents. However, if the fish escapes from the damaged of aquaculture net cage, the wild fish populations will be threatened. In this paper, the dynamic model of the circular net was developed in steady current using lumped mass method. In order to validate the numerical model, the deformations of netting were compared with the physical model test and the numerical results by other authors. Then the dynamic result of flexible twine damaged could be obtained by numerical simulation analysis in current. The variety of netting deformation, the tension distribution of the circular net and the force of netting twine connected the floating collar were analyzed. The result show that the flexible twine damaged will lead to the local variable. This study is helpful for the predication of flexible twine damaged through measure the force distribution of floating collar.

1. Introduction

Aquaculture farming is playing an important role in the future, and can provide more and more the marine food for human consumption. There is a trend of moving marine fish farms to more exposed areas. The aquaculture net cage must face the larger waves and stronger currents. So the aquaculture net cage will faced with huge threat. Once aquaculture net cage is damaged or collapsed leading to fish escaping. The wild fish populations will be threatened and the fish farmers have economic losses. Thence the predication of flexible twine damaged can through measure the force distribution of floating collar.

Many scholars have studied the hydrodynamic characteristics of net [1-4]. In order to making the established models more realistic, the numerical models of the net were optimized through compared with the test data. Lee et al. [5] calculated the dynamic behavior of net using implicit integration method. Huang et al. [6, 7] studied the dynamic response of the gravity cages by the lumped-mass method in currents. Cifuentes et al. [8] designed the complex cage system using Morison force model with variations Cd according to high solidity ratio and current speed. Moe-Føre et al. [9] established the numerical model for high solidity net cage at high flow velocities considering the changes in water flow and the global drag coefficient of the net. Ma et al. [10] proposed an innovative hybrid method to simulate the interaction between net and water flow. Yao et al. [11] used novel hybrid volume approach to establish the calculation model of net under the current load.
The research subjects are focus on the hydrodynamic characteristics of net cage. According to the statistical analysis, which two-thirds of the escape incidents and number of escaping fish are due to hole in the net, damage of net is the main reason for the escape of fish [12]. So this paper will developed the dynamic model of aquaculture net cage considering flexible twine damaged. Through compared with the physical model test and the numerical results by other authors, the results of numerical model are compared in this paper. The netting deformation, the tension distribution of the circular net and the force of netting twine connected the floating collar are obtained using numerical simulation analysis.

2. Numerical model

In this paper, the flexible net was simplified mass-spring model using lumped mass method as shown in Figure 1. Only considering the steady current, the forces of each knot can be expressed in the Figure 1 including the gravitational force $W$, buoyant force $B$, drag force $F$ and tension force $T$. Therefore, the motion equation of circular net can be described as:

$$ M \frac{\partial q(t)}{\partial t} = W(t) + B(t) + F(t) + T(t) $$

Where, $M$ is the mass of the mesh knot, $q(t)$ is the velocity of mesh knot.

![Figure 1. The force of mesh knot in mass-spring model of flexible net](image)

The gravitational force of mesh knots:

$$ W = m_i g $$

where, $g$ is the acceleration of gravity. The value in this paper is $9.81 m/s^2$.

The buoyant force of mesh knots:

$$ B_i = \rho g \forall_i $$

where, $\rho$ is the density of the water; $\forall_i$ is the volume of water that the node discharges.

The tension between node $i$ and adjacent node $j$ ($j=1, 2, 3, 4$) can be calculated as following

$$ T_{ij} = \begin{cases} AC_i \left(\frac{l_{ij} - l_0}{l_0}\right)^{C_1} & l_{ij} > 0 \\ 0 & l_{ij} \leq 0 \end{cases} $$

where, $l_0$ is the original length of among knots, $l_{ij}$ is the length after deformation, i.e. $l_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}$ ($i,j = 1,2,3,4$), $A$ is the sectional area of the mesh knots, and $C_1$ and $C_2$ are the elastic coefficients of the flexible net material. According to Fibre Ropes for Fishing
Gear by Klust [13], the elastic coefficients of polyethylene (PE) material are given as $C_1 = 3.454 \times 10^8$ and $C_2 = 1.0121$.

**Figure 2. Relation between a flexible net cage and fluid flow**

The current is assumed to be steady and uniform, so the inertial force is neglected. Figure 2 shows the relationship between a flexible net cage and steady current. Assuming a water particle is moving into the net cage with a relative velocity $U_R$ to the net panel. The drag force and lift force can be expressed as:

$$
\begin{align*}
F_{Dn} &= \frac{1}{2} \rho C_D A_p U_R \left| U_R \right| n_D \\
F_{Ln} &= \frac{1}{2} \rho C_L A_p U_R \left| U_R \right| n_L
\end{align*}
$$

where, $C_D$ is the drag force coefficient, $A_p$ is the projected area of the mesh knots, $U_R$ is the relative velocity of the fluid flow and the mesh knots, $C_L$ is the lift force coefficient.

**3. Numerical simulations and results**

In order to verify the accuracy of the numerical calculation model, the numerical results were compared with the data of physicals experimental model by Lader and Enerhaug [14]. The physicals experiment net was made up of two rectangular net. Each rectangular net was 81 meshes high and 125 meshes wide. The material of the flexible net was nylon (PA). The grid had a side length of 16mm and the twine thickness was 1.8mm. The diameter of the circular net was 1.435m and its height was 1.44m. The weight was composed of 16 weights evenly distributed at the bottom of the circular net and the mass of each weight has 400g. The current velocities of test were 0.21m/s and 0.33m/s, respectively. Figure 3(a) shows the experimental results by Lader and Enerhaug [14], Figure 3(b) shows the numerical results by Zhao et al. [15], Figure 3(c) show the numerical results of this paper. From Figure 3 and Table 1, it can be seen that the numerical results agreed well with the experimental datas, indicating that the numerical calculation method used in this paper is reasonable.

In this paper, the shape of element in circular net is diamond. The diameter of floating collar at the top of the net is 1.435m and 32 weights are evenly distributed at the bottom of the net with fixed [16]. The mass of each weight is 200g. The different current velocity (0.22m/s, 0.33 m/s, and 0.44m/s) were used to impact the flexible net, respectively. The other parameters using in simulation are listed in Table 2.

**Table 1. Comparison of volume reduction rate and drag force on the net between calculated and experimental results**

| Velocity/ (m/s) | Volume reduction rate |drag force/N |
|-----------------|-----------------------|-------------|
|                 | Experiment/ Calculation/ Absolute error/% | Experiment/ Calculation/ Absolute error/% |
| 0.13            | 3% 1% 2 | 12.02 11.27 6% |
| 0.21            | 9% 5% 4 | 21.97 23.4 7% |
| 0.26            | 14% 11% 3 | 34.96 35.88 3% |
| 0.33            | 23% 24% 1 | 49.79 57.82 16% |
Figure 3. The deformation of circular net in different steady current

Table 2. The parameters using in simulation

| Item   | Material | Height of net(m) | The density of PE(kg/m³) | Mesh size(mm) | Diameter of twine(mm) | Density of water(kg/m³) |
|--------|----------|------------------|--------------------------|---------------|-----------------------|------------------------|
| Condition | PE       | 1.44              | 953                      | 45            | 1.8                   | 1025                   |

The circular net has so many nodes, which leads to inefficient computing. So the neighboring 5x5 mesh is equivalent to a large mesh using the mesh grouping method [17]. The structural model is shown in Figure 4(a) and the flexible twine damaged model is shown in Figure 4(b).

Figure 4. Structure of circular net
From Figure 5, there is not much difference in the deformation of undamaged and damaged flexible net. Because the flexible net is round, it is inconvenient to observe tension distribution on netting. Therefore, from the demarcation 1 between the upstream net and the downstream net, it is unfolded in a counterclockwise direction to obtain a plane expanding view of the netting forces, which were shown in Figure 6.

The right part of Figure 7 shows tension distribution at the upstream net and the left part shows tension distribution at the downstream net. The forces on the upstream net and the downstream net of undamaged circular net are symmetrically distributed. If the twine is damaged, the force in the damaged area will change. The tension force of the damaged diagonal twine is reduced, but the tension force of the adjacent diagonal line parallel is increased. The other forces are almost unchanged. The result is shown in Figure 8.

(a) The deformation of undamaged circular net (b) The deformation of damaged circular net

**Figure 5.** The steady shape of circular net in current

**Figure 6.** The unfolded method of circular net (top view)

(a) The tension distribution of undamaged circular net
Figure 7. Tension distribution of circular net

Figure 8. Difference between condition of netting with undamaged and damaged (Partial enlargement view)

Tension forces distribution of twine on floating collar are shown in Figure 9. Under normal circumstances, the force on the net is not easy to obtain. Therefore, we can use the tension force on the floating collar to predict the change of force on the net. From Figure 9, the oblique direction in which the tension is reduced is the direction of the damage. According to the direction, the damaged circular net can be found for reduce losses.
The static character of floating collar

4. Conclusion
The dynamic characteristic of circular net with twine damaged in net cage under steady current is studied. The mathematical model of the system is established using lumped mass method. The shape of circular net, tension force distribution on the twine and floating collar are obtained by numerical analysis. Single twine damaged has little effect on deformation of circular net. The tension forces of twine are changed on the local area of twine damaged especially adjacent diagonals. The tension forces of floating collar are symmetrical without damaged, but the tension forces would be changed with damaged. The oblique direction in which the tension is reduced is the direction of the damage, and adjacent diagonals direction the forces is increased. So the forces can be measured by sensor in order to judge if the twine is damaged. The work is very useful for predict the damage direction of circular net cage.

Acknowledgements
The research was supported by the National Natural Science Foundation of China (Grant No.51175484), the Fundamental Research Funds for the Central Universities (Grant No.201513053) and the Key Laboratory for Mechanism Theory and Equipment Design of Ministry of Education (Tianjin University).

References
[1] R Wan, F Hu and T Tokai 2010 Fisheries Sci. 68(4) pp 815 – 823
[2] Tsukrov I, Eroshkin O, Fredriksson D, Swift M R and Celikkol B 2003 Ocean Eng. 30 pp 251 – 270
[3] Zhan JM, Jia XP, Li YS, Sun MG, Guo GX and Hu YZ 2006 Aquacult Eng. 35 pp 91 – 101
[4] Zhao YP, Gui FK, Xu TJ, Chen XF and Cui Y 2013 *Appl. Ocean Res.* **39** pp 158 – 167
[5] Lee CW, Lee JH, Cha BJ, Kim HY and Lee JH 2005 *Ocean Eng.* **32** pp 331 – 347
[6] Huang CC, Tang HJ and Liu JY 2006 *Aquacult. Eng.* **35** pp 258 – 270
[7] Huang CC, Tang HJ and Liu JY 2007 *Aquacult. Eng.* **37** pp 144 – 157
[8] Cifuentes C and Kim MH 2017 *Ocean Systems Eng.* **7**(2) pp 143 – 155
[9] Moe-Føre H, Lader PF, Lien O E and Hopperstad S 2016 *J. Fluid. Struct.* **65** pp 180 – 195
[10] Ma L, Hu K, Fu S, Moan T and Li R 2016 *J. Ship Res.* **60** pp 14 – 29
[11] Yao YM, Chen YL, Zhou H and Yang HY 2016 *J. Fluid. Struct.* **62** pp 350 – 366
[12] Jensen O, Dempster T, Thorstad EB, Uglem I and Fredheim A 2010 *Aquacult. Env. Interac.* **1** pp 71 – 83
[13] Klust G 1983 *Fibre ropes for fishing gear* (Madras, India)
[14] Lader PF and Enerhaug B 2005 *IEEE J. Oceanic Eng.* **30**(1) pp 79 – 84
[15] Zhao YP, Li YC, Dong GH, Gui FK and Teng B 2007 *Aquacult. Eng.* **36** pp 285 – 301
[16] Huang XH, Guo GX, Hu Y and Tao QY 2010 *J. Fishery Sci. China* **17** pp 312 – 319 (in Chinese)
[17] Su W and Zhan JM 2007 *J. Hydrodyn.* **22** pp 267 – 272 (in Chinese)