1) Title
Validity and visualization of a numerical model used to determine dynamic configurations of fishing nets

2) Running Title
Numerical model of nets

3) Authors and their Affiliations
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ABSTRACT

Our objective was to develop a numerical calculation method to simulate the three-dimensional dynamic behavior of fishing nets. In a previous study, we presented a formulation to calculate net configurations. In this method, fishing nets were modeled as a group of lumped mass points interconnected with springs that have no mass. To verify the validity of calculation results by using computational model, we carried out the flume tank experiments with a rectangular net and compared results of the numerical simulation of experiments. Using our method, numerical calculations for a rectangular net in a steady flow can provide accurate results. The calculated load and tension force distribution of the flat net were generally in accordance with the results of the flume tank experiments. This study shows that our method is valid for the simulation of fishing nets; furthermore, we have resolved earlier problems that were associated with this model.

Key Words: fishing gear, lumped mass model, numerical simulation, supple net

INTRODUCTION

Most parts of gear that is currently used for fishing are made from supple nets. The action of external forces shapes an infinitely flexible structure, such as a fishing net into a variety of configurations. To improve fishing selectivity and optimal design techniques for developing appropriate fishing nets, it is important to estimate the behavior and detailed physical properties relating to a net.

In Japan, few investigators have ever attempted to simulate the dynamic behavior of fishing net shape. In Europe, scientists from a number of research institutes for fishing gear technology have developed trawl net-shape simulators by using PCs. Although these investigations are interesting and progressive[1-4], we believe that several problems remain, notably, that the researchers have not adequately compared the calculated results of the simulations to those of actual experiments. We therefore consider that theoretical methods of simulating net shapes are still in the process of being developed.

Our objective was to develop a generalized numerical model and analysis system "NaLA" (Net Shape and Loading Analysis System) to simulate the three-dimensional dynamic behavior of fishing nets. NaLA is composed of three applications: the preprocessor that makes it easy to create initial parameters of fishing nets, the application that calculates the behavior of nets, and the applications that visualizes the calculation results as 3D graphics. In previous papers[5,6], we presented a model to estimate net configurations and showed the results as a three-dimensional image on a PC. Consequently, we verified that the numerical simulation was realistic and highly accurate with regard to net shape, and we considered that analysis using this model was useful and accurate enough for practical application. However, in those papers[5,6], we did not describe accurate comparisons in more detail, for example, the tension loads of a net.

In this study, we carried out tank experiments and compared the net configurations and loads of the experimental results with those of the calculated results under the same conditions, in order to examine the accuracy of the estimated results presented in our previous paper in more detail.

MATERIALS AND METHODS

Numerical Calculation Method

By applying a lumped mass model, we assumed that a net is a connected structure with limited mass and spring.[7] Lumped mass points are set at each knot and in the center of each mesh bar (Fig. 1). It is assumed that the mass points of knots are spherical, in which fluid force coefficients of each direction are constant, and that mass points of mesh bars are cylindrical elements, which means that the direction of fluid forces must be considered. Since the calculation method that uses this model has been fully explained in our previous paper[5,6], we describe here only a brief outline.

The Equation of Motion for Net

We assume that the fishing net is set in a spatially and temporally uniform current flow. The motion of point *i* can be expressed by the following equation.

$$(M_i + \Delta M_i)\boldsymbol{\alpha} = \boldsymbol{T} + \boldsymbol{D} + \boldsymbol{W} + \boldsymbol{B} \qquad (1)$$

where $\boldsymbol{\alpha}$: acceleration vector of point *i*, $\boldsymbol{T}$: tension force acting on point *i*, $\boldsymbol{D}$: drag force, $\boldsymbol{W}$: gravity force, $\boldsymbol{B}$: buoyancy force. M_i and ΔM_i are the mass of point *i* and the added mass of *i*, respectively.

The direction of the fluid forces on the mass points in each mesh bar must be considered, because mesh bars are assumed to be cylindrical elements. For a simplified formulation, we define the local coordinate axis passing through point *i* τ , η, and ξ (Fig. 1). The η axis is defined on a plane including the τ axis and the velocity vector $\boldsymbol{V}$ of water flow. $\boldsymbol{V}$ can be broken down into τ (tangential) and η (normal) components; thus, we can estimate the total fluid force on the plane by defining only τ and η components of the fluid force. We can therefore assume that the fluid force coefficients (C_D and C_M) of τ and η components are treated as constant values. The magnitude of the tension force T_{ij} on point *i* from *j* is given by

$$T_{ij} = E_{ij} S_{ij} \frac{\Delta l_{ij}}{l_{ij}} \qquad (2)$$

where, E_{ij}: Young's modulus of the spring, S_{ij}: cross section of the spring, Δl_{ij}: extension of the spring, l_{ij}: the original spring length. The unit vectors from *i* to 1 and 2 are defined $\mathbf{e}_{i1}$ and $\mathbf{e}_{i2}$, and the unit vector along τ, η, and ξ components are defined $\mathbf{e}_\tau$, $\mathbf{e}_\eta$, and $\mathbf{e}_\xi$ respectively; thus, the τ-component drag force of *i* can be represented by:

$$T_\tau = T_{i1}\mathbf{e}_{i1} \cdot \mathbf{e}_\tau + T_{i2}\mathbf{e}_{i2} \cdot \mathbf{e}_\tau \qquad (3)$$

where, $[\cdot]$ represent the scholar product. The same representation can be applied for the other tension forces (T_η and T_ξ) of η and ξ components.

The τ, η, and ξ-components' relative velocity of *i* is $\dot{\tau} - \mathbf{e}_\tau \cdot \boldsymbol{V}$, $\dot{\eta} - \mathbf{e}_\eta \cdot \boldsymbol{V}$ and $\dot{\xi}$ respectively; thus, the τ-component drag force of *i* can be represented by:

$$D_\tau = -0.5 \rho C_{D\tau} S_\tau \left| \dot{\tau}_i - \mathbf{e}_\tau \cdot \boldsymbol{V} \right| \left(\dot{\tau}_i - \mathbf{e}_\tau \cdot \boldsymbol{V} \right) \qquad (4)$$

where $C_{D\tau}$ and S_τ represent the drag coefficient and projection area of the τ-component, respectively. The same representation can be applied for the other drag forces (D_η and D_ξ) of η and ξ components.

As the other external forces $\boldsymbol{B}$, and $\boldsymbol{W}$, can be expressed in the local coordinate system, we can represent the equation of the τ -component motion of point i by:

$$\left(M_i + \Delta M_{\tau i}\right)\ddot{\tau}_i = T_\tau + D_\tau + W_\tau + B_\tau \qquad (5)$$

where $\Delta M_{\tau i}$ is the τ -component added mass. Thus, in the same manner we can also express the motion of the equation in η and ξ directions. Transformations of global coordinates can be given by the following equations:

$$\begin{pmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{z}_i \end{pmatrix} = \begin{pmatrix} x_\tau & x_\eta & x_\xi \\ y_\tau & y_\eta & y_\xi \\ z_\tau & z_\eta & z_\xi \end{pmatrix} \begin{pmatrix} \dot{\tau}_i \\ \dot{\eta}_i \\ \dot{\xi}_i \end{pmatrix} \qquad (6)$$

where x_τ and so on are *x*, *y*, and *z*-components of unit vectors of τ , η , and ξ -directions. Consequently, the following ordinary differential equations can be obtained:

$$\begin{aligned} \frac{d\dot{x}_i}{dt} &= f\left(x_i, y_i, z_i, \dot{x}_i, \dot{y}_i, \dot{z}_i, x_1, y_1, z_1, x_2, y_2, z_2; t\right) \\ \frac{d\dot{y}_i}{dt} &= g\left(x_i, y_i, z_i, \dot{x}_i, \dot{y}_i, \dot{z}_i, x_1, y_1, z_1, x_2, y_2, z_2; t\right) \\ \frac{d\dot{z}_i}{dt} &= h\left(x_i, y_i, z_i, \dot{x}_i, \dot{y}_i, \dot{z}_i, x_1, y_1, z_1, x_2, y_2, z_2; t\right) \end{aligned} \qquad (7)$$

$$\frac{dx_i}{dt} = \dot{x}_i$$
$$\frac{dy_i}{dt} = \dot{y}_i \qquad (8)$$
$$\frac{dz_i}{dt} = \dot{z}_i$$

The net shape of each time step can be calculated numerically by solving an ordinary differential equation given an initial condition. The equations were solved using the Runge-Kutta-Verner fifth-order and sixth-order method with variable step-size as kept the global error proportional to 1.0×10^{-2}.

An Application to Visualize Net Shape Configuration

To be more generally applicable and convenient for a post-processor, we used OpenGL library software to develop a three-dimensional visualization application program to determine the net configuration; we visualized net shape with the Compaq Array Viewer in our previous paper. A net is drawn by connecting each mass point by segments that are color-coded by tension of line; we can therefore easily see the distribution of tension on a net, based on color changes in the mesh bars. Figures 2, 3, and 4 show examples of 3-D graphics of a box-shaped net cage configuration using OpenGL. This application does not only visualize the dynamic behavior of fishing gear, it also shows the net shape at arbitrary time intervals, by going forward or backward. The 3-D graphics of the net shape can also be expressed as dynamic images over time using this program on a PC (Fig. 3). An expanded view of parts of the net can be obtained, and the viewpoint can be changed in any desired direction (Fig. 4). However, collisions with other net panels and the water flow decrease caused by the front net panel are not taken into account the calculation model here. Those problems remain to be solved.

Flume Tank Experiments

We carried out experiments to examine the validity of our model by comparing the shape and tension loads of the actual net with calculation results using the model. We used the horizontal circular flume tank at Hokkaido University (6.0 m long, 2.0 m wide, 1.0 m deep). Three types of nylon nets, types A, B, and C (Table 1) were used. Each net was set at a water depth of 1.0 m inside the flume tank. Six points on the top of each net were fixed to a steel rod (1.5 m long) on the water surface, and the two bottom corners were fixed to two sinkers under the flow (Fig. 5). The flow speed was set at 16.1, 19.5, 23.7, 28.0, 32.4, 36.9 and 40.9 cm/s. We recorded the net shape when it was in counterpoise, on a digital video camera through an observation window.

Experiments were carried out to measure loads and tensions acting on the net in steady flow, simultaneously. The load cell was installed in the center of the steel rod on which the net was fixed, and strain gauges were attached to measure tension forces at three points on the top edge (Fig. 5).

Numerical Simulation

This calculation was conducted using the same conditions as those in flume tank experiments, to compare the experimental results of the net shape, tension and load with calculated results. Initial parameters (mass and projection area) of particles are shown in Table 2. With reference to results for the dependence of the drag coefficient for a smooth sphere C_D on the Reynolds number *Re* in the form of a curve, and Bessonneau and Marichal's study[1], we applied drag and added mass coefficient values to the calculation as follows. For mass points of knots, we used $C_D = 1.0$ and $C_M = 0.5$ for each component. In addition, for mesh bars, we used $C_D = 0.1$ and $C_M = 0.0$ for the τ component, and $C_D = 1.2$ and $C_M = 1.0$ for the η and ξ components. We used as Young's modulus in Equation (2) the value of Nylon (i.e., 1.2×10^9 Pa). Initial position of a rectangular net was upright toward the flow.

RESULTS AND DISCUSSION

Comparison of net configurations

We compared net shapes from the experiment with those from calculations. Fig. 6-a shows a video image of the Type-C net configuration in the flume tank experiment at a water velocity of 16.1 cm/s; Fig. 6-b shows a 3-D graphic of the numerical simulation results in an equilibrium state under the same conditions. We obtained close agreement between the experimental and calculated results. Other numerical results of net shape were also similar to those of experiments.

To compare the calculated results of net shape in more detail, we used video image analysis to measure parts of the net in Fig. 6-a, and calculated the dimensionless quantities B/A_2, C/A_1, D/A_2, and E/A_1. We corrected each dimensionless quantity by the aspect ratio of a square board that has been set on some places in flume tank in order to eliminate the influence by the distortion of images. Regardless of net type, we confirmed that each dimensionless quantity, B/A_2, C/A_1, D/A_2, and E/A_1, was in good agreement, and the error of each calculated value when compared with an experimental result was 0.05 or less (Fig. 7). Thus, we believe that simulation using this method of calculation can express net configurations with a high degree of accuracy.

Comparison of line tension

Fig. 8 shows a comparison of the experimental and calculated results for the horizontal component of the loads on the steel rod at each flow speed and with each net type. The average of calculated results of types A, B, and C were estimated to be 0.80, 0.98, and 0.94 times those of experimental results, respectively; namely, very close agreement between the experimental and calculated results was obtained at each water velocity in the case of Type-B and C. That close agreement between each result was obtained, though our model is more underestimated than other two cases. We therefore suggest that numerical calculation of loads on nets of any mesh size can provide good results, using this method. In this study, we used nets that had mesh bars of the same diameter. It remains to be investigated whether calculated results will vary with different bar diameters.

Fig. 9 shows a comparison of the experimental and calculated results for the tension of line on T_1, T_2, and T_3 in Figure 5 at each flow speed and with each net type. The values of T_1 in the cases of each net type exhibited similar tendencies. Close agreement between experimental and calculation results was obtained from T_1, T_2, and T_3 of Type-C. However, disagreement between those results was obtained from T_2 and T_3 of Type-A and B. This result suggests that mesh bars along diagonal line of the rectangular net in calculation results is being more extended than in experimental results. Additionally, we compared the calculated tension force distribution on the steel rod with the experimental results by examining the tension at three points on the steel rod that was attached to the topside of the net. The ratios of tension force at each point to the sum of tensions that act on the rod are described as R_1, R_2, and R_3, such that

$$R_i = \frac{T_i}{T_1 + T_2 + T_3} \quad (i = 1, 2, 3) \qquad (7)$$

where T_i is the tension of i.

R_1 was larger than the other two values in all cases with regard to the experiment and the model. R_1 of the experiment varied between 0.45 and 0.65, and R_1 of the model varied between 0.45 and 0.49 (Fig. 9). R_2 and R_3 were similar to each other; values in the experiment varied between 0.15 and 0.30, and values in the model varied between 0.20 and 0.28 (Fig. 10). These results suggest that load was concentrated on the outside top of the net in both the simulation and the flume tank experiment. In the experiment with all nets, there was no significant relationship between water velocity and R_1, R_2, or R_3. Likewise, there was no significant relationship in the model; the ratios did not vary with varying water flow. Very close agreement between experimental and calculation results was obtained from R_1, R_2, and R_3 at each velocity in the case of Type-C. However, close agreement was not obtained from R_1 in the case of Type-A and B. It is necessary to discuss whether the disagreement was caused by the simplification of calculating.

In the model result of the Type-C net in 16.1 cm/s water flow, concentrated load acted on the diagonals of the net (Fig. 11); this was similar to the model results of the other nets. Thus, fairly close agreement was obtained in the experimental and model results for the tension distribution in a net.

Our method was able to estimate the detailed net shape and the loads on the net under any conditions, and we obtained close agreement between experimental and model results with regard to the tension load distribution on the net. However, the calculation required a considerable investment of time, because the fishing net was modeled as a large number of mass points, equal to the number of knots and mesh bars. Therefore, it is necessary that calculation models with grouped mass points are used appropriately, by taking the desired accuracy of the estimation into account.

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FIGURE CAPTIONS

Fig. 1. Schematic diagram of the model, taking into consideration changes in fluid dynamic coefficients with current direction.

Fig. 2. Opening screen of the 3D visualization using the OpenGL library.

Fig. 3. Simulated dynamic behavior of the net cage in water flow.

Fig. 4. Expanded view of parts of the net cage.

Fig. 5. Schematic diagram of the devices used in the flume tank experiments.

Fig. 6. (a) Digital video image of the experiment with a Type-C net in 16.1 cm/s water flow. We measured the lengths of A_1, A_2, B, C, D, and E from digital video images in order to compare net shapes based on experimental results and simulation results.
(b) Side view of a 3D graphic of the simulation with a Type-C net in 16.1 cm/s water flow.

Fig. 7. Relationship between each dimensionless quantity and water velocity for each net type.

Fig. 8. Relationship between the flow component for loads acting on the steel rod for each net type and the water velocity.

Fig. 9. Relationship between tensions of each line on T_1, T_2, and T_3 for each net type and the water velocity.

Fig. 10. Comparison of the relationship between tension distribution on the top edge of the net and water velocity for each net type.

Fig. 11. 3D graphic of the simulation with a Type-C net in 16.1 cm/s water flow.

Table 1. Net types used in the experiments.

Table 2. Calculation conditions for each net type.