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# A method for improving the simulation efficiency of trawl based on simulation stability criterion

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ABSTRACT

The lumped-mass method is one of the most fundamental methods to simulate the dynamic behavior of submerged flexible nets. However, the low calculation efficiency limits its applications. In order to improve the calculation efficiency, the numerical stability of lumped-mass method based on explicated Euler integral algorithm was investigated. The simulation stability criterion was derived as a function of simulation step size and the physical parameters of netting materials. A physical parameter optimization (PPO) method was put forward to calculate the desired values of the lumped-mass model's physical parameters based on stability criterion; length compensation was implemented to compensate the extra deformation of mesh bars caused by the changes of their stiffness. The PPO method can ensure the stability of the lumped-mass model with a desired simulation step size while minimizing the change to the physical parameters. A lumped-mass model of trawl gear was established with the PPO method, the simulation results were compared with those of the conventional lumped-mass method (without PPO) to validate the improvements. By using the PPO method, the calculation efficiency can be accelerated by 40 times while only inducing less than 2% error to the simulation results.


## 1. Introduction

There are many ropes and netting structures in ocean engineering applications such as fishing gear (trawl gear, purse seine gear, tuna longline gear, etc.). Engineers need to know the dynamics of those structures in order to have better control of them and gain better performance in usage. But the strong nonlinearity in both geometry and hydrodynamic force makes those structures very hard, even impossible to get an analytical result. The lumped-mass method is one of the most fundamental methods to simulate both the dynamic and static behaviors of submerged flexible netting structures. The lumped-mass method uses several interconnected mass spring elements to simplify the flexible netting structures; it concentrates the distributed hydrodynamic force, buoyancy and gravity of the net to the lumped point masses and treats the mesh bar as a massless spring. Existing researches have already built some lumped-mass models for tuna longline gear (Lee et al., 2005b), purse seine gear (Kim et al., 2007; Kim and Park, 2009), fish cage (Lee et al., 2008a; Suzuki et al., 2009) and trawl gear (Khaled et al., 2013; Chen et al., 2014).

A lumped-mass model of trawl net generally has thousands of knots and bars, even when the model is simplified; this makes many equations to be solved per calculation step. In many applications such as fishing state estimation (Suzuki and Takagi, 2008; Reite, 2009) and training simulator (Sun et al., 2011), where a real-time simulation is required, the calculation efficiency is especially emphasized. Typically, the lumped-mass method is considered to be computationally expensive because it tends to be unstable when large step size is employed. Walton and Polachek (1960) investigated the numerical stability of a two dementional submerged cable. The numerical stability criterion was derived as a function of the cable segment's mass, length and tension. Huang (1994) further elaborated the numerical stability analysis of three dementional submerged cables and obtained similar results. Both of their results were based on neglecting the effect of added mass and hydrodynamic force. Johansen (2007) studied the numerical stability of ideal cables using Courant number and suggested to use two different spatial grids to model the cable's axial and transversal dynamics separately. Although some stability criterions have been dirived for marine cables, there does not exist any numerical stability analysis for submerged netting structures. However, several methods to improve the calculation efficiency have been implemented. Generally, those methods can be divided into two categories. One is to use more suitable numerical integral algorithms and the other is to rearrange and/or simplify the netting structures.

The governing equations of the lumped-mass model generally have strong nonlinearity and high stiffness, especially when the

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model is divided into very small elements. Thus an explicit algorithm will be restricted to a rather small step size while an implicit algorithm can offer a relatively larger step size. To this end, the Newmark-β algorithm (Tsukrov et al., 2003; Lee et al., 2005a, 2005b; Sun et al., 2011) and backward Euler algorithm (Kim et al., 2007) were employed to solve the lumped-mass model. However, in an implicate algorithm, the calculation of state variables requires a lot of iterations, which is very hard to converge because of the huge scale and discontinuity of the governing equations (Howell, 1991). Therefore, some researchers prefer an explicit algorithm such as Runge–Kutta algorithm (Suzuki et al., 2003; Zhu et al., 2006; Lee et al., 2008a; Kim and Park, 2009; Hosseini et al., 2011). Nevertheless, neither the implicit nor explicit algorithms have an outstanding advantage in calculation efficiency. Besides more suitable numerical integral algorithms, other approaches have also been used to improve the calculation efficiency. Mesh grouping method is used in almost every lumped-mass model to reduce the number of knots and bars involved in numerical calculation (Bessonneau and Marichal, 1998; Takagi et al., 2004; Li et al., 2006; Lee et al., 2008a; Park, 2014). Existing researches show that with a reasonable mesh grouping method, the simulation results will be accurate enough (Takagi et al., 2004). Lee et al. (2008b) improved the calculation efficiency and the graphical representation by adding non-active nodes to the model. The simulation time was reduced about 30% and a more accurate net shape representation was reported. Zhang et al. (2012) introduced a matrixing network which is a highly efficient data structure to improve calculation efficiency, but the detailed improvement was not stated clearly.

Through a numerical stability analysis of netting structure's lumped-mass model, this paper derived the stability criterion based on the net's physical parameters. A physical parameter optimization (PPO) method which can improve calculation efficiency was then put forward. Based on the stability criterion, the PPO method can optimize the physical parameters which are not so important to the trawl net's dynamics, but can significantly affect the numerical stability. The stiffness of the mesh bars was also optimized to meet a larger step size and length compensation was employed to make sure the elastic deformation of the mesh bars remained unchanged.

## 2. Material and methods

### 2.1. Mathematic model of trawl net

In this paper, the trawl net was described as interconnected mass spring damper elements, the knots of the net were considered as mass points and the mesh bars were considered as springs without mass, the inner damping effect of the mesh bars was also taken into consideration (Fig. 1). For simplicity, the knots were assumed to be spherical points and the mesh bars were assumed to be cylinders. The external forces exerted on the mesh bars, such as hydrodynamic force, buoyancy, and gravity, were distributed equally to its two end knots.

#### 2.1.1. Forces acting on knots

The total forces $\mathbf{F}_k$ acting on a knot can be expressed by the following equation:

$$\mathbf{F}_k = \Sigma\mathbf{T} + \mathbf{H} + \mathbf{G} + \mathbf{B} \tag{1}$$

where $\mathbf{T}$ is the tension force of the mesh bars which are connected to the knot, $\mathbf{H}$ is the hydrodynamic force, $\mathbf{G}$ is the gravity and $\mathbf{B}$ is the buoyancy. The sinking force of sinkers and the buoyancy of floats are included in $\mathbf{G}$ and $\mathbf{B}$.

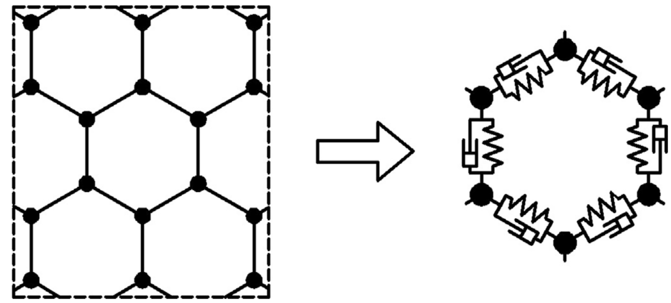

**Fig. 1.** Mass spring representation of netting structures. This figure illustrates the mass spring model of a hexagon net mesh. The left part is a segment of fishing net, the right part is the mass spring model. The damping effect of the mesh bars is also taken into consideration.

The tension force of mesh bars can be expressed as

$$\mathbf{T} = \mathbf{T}_e + \mathbf{T}_c \tag{2}$$

where $\mathbf{T}_e$ is the elastic force which is proportional to the strain, $\mathbf{T}_c$ is the inner damping force which is proportional to the mesh bar's length change rate. They can be represented by the following equations:

$$\mathbf{T}_e = \begin{cases} -EA\cdot\dfrac{|\mathbf{r}| - l_0}{l_0}\cdot\dfrac{\mathbf{r}}{|\mathbf{r}|} & |\mathbf{r}| > l_0 \\ 0 & |\mathbf{r}| \le l_0 \end{cases} \tag{3}$$

$$\mathbf{T}_c = -c_l\cdot\frac{\mathbf{r}\cdot\Delta\mathbf{u}_k}{|\mathbf{r}|}\cdot\frac{\mathbf{r}}{|\mathbf{r}|} \tag{4}$$

where $E$ is Young's modulus, $A$ is the cross-section area of mesh bar, $\mathbf{r}$ is the position vector between two end knots, $l_0$ is the initial length of mesh bar, $c_l$ is the inner damping coefficient of mesh bar, $\boldsymbol{\Delta}\mathbf{u}_k$ is the relative velocity vector between two end knots.

The hydrodynamic force $\mathbf{H}$ acting on the knots can be described as

$$\mathbf{H} = -\frac{1}{2}C_D\rho A\mathbf{u}_k^2\cdot\frac{\mathbf{u}_k}{|\mathbf{u}_k|} \tag{5}$$

where $C_D$ is the drag coefficient of knot which equals 1.0 (Takagi et al., 2004), $\rho$ is the density of the surrounding water, $A$ is the project area of knot; $\mathbf{u}_k$ is the resultant velocity vector.

#### 2.1.2. Forces acting on mesh bars

There are different kinds of forces acting on mesh bars: the hydrodynamic force $\mathbf{H}$, the gravity $\mathbf{G}$ and the buoyancy $\mathbf{B}$. The external forces exerted on the elements of warps, headline and footrope were calculated in the same way as mesh bars. The hydrodynamic force $\mathbf{H}$ consists of the form drag force $\mathbf{F}_P$ and the viscous friction force $\mathbf{F}_f$ (Fig. 2). $\mathbf{F}_P$ is in the same plane with the resultant velocity vector $\mathbf{u}_m$ and the mesh bar's position vector $\mathbf{r}$, it is perpendicular to $\mathbf{r}$ and forms an obtuse angle with $\mathbf{u}_m$. $\mathbf{F}_f$ is parallel with $\mathbf{r}$ and forms an obtuse angle with $\mathbf{u}_m$. The resultant velocity vector $\mathbf{u}_m$ can be expressed by the velocity vector of two end knots $\mathbf{u}_{ka}$, $\mathbf{u}_{kb}$ and the velocity of seawater $\mathbf{u}_w$:

$$\mathbf{u}_m = (\mathbf{u}_{ka} + \mathbf{u}_{kb})/2 - \mathbf{u}_w \tag{6}$$

The form drag force $\mathbf{F}_P$ and the viscous friction force $\mathbf{F}_f$ are proportional to the component of $\mathbf{u}_m$ which is along their directions. They can be expressed as

$$\mathbf{F}_P = C_{N90}\cdot\frac{\rho(\mathbf{u}_m\cdot\sin\alpha)^2}{2}\cdot S_N\cdot\mathbf{n}_P \tag{7}$$