Numerical Simulation of Deep-Towed Streamer Cable in Ocean Current by ALE Finite Element Method

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***Abstract*- High frequency seismic reflection surveys using deep-towed streamers are now of interest to explore sub-seafloor structures bearing hydrothermal deposit with adequate resolution. One of the problems arose with the utilization of the deep-towed streamer is the navigation or the location estimation of seismic sources and streamers to assure the necessary resolution. The estimation errors in the positioning come from the inaccurate acoustic positioning and from cable feathering, *i.e.*, waving of the towed streamer cable in the ocean current. It is inevitable to minimize the positioning error of the location of the sources and the streamers to enhance the resolution of deep-towed surveys.**

Since a streamer waves due to the interaction of the streamer cable with the drag force in the seawater, it is necessary to estimate the behavior of the streamer when towed. For simulating the behavior of the streamer cable in a kinematic way, we employed a finite element method using arbitrary Lagrangian - Eulerian (ALE) finite element formulation in the fluid domain, and total Lagrangian formulation for the cable. The geometrical compatibility conditions and the equilibrium conditions on the interface are automatically established by equating the displacement, velocity and acceleration on the interface common to the fluid and the cable.

Finally, we confirmed that our numerical simulations reproduce the cable feathering behavior. Our results demonstrate that the drag force and the positioning error are strongly dependent not only on the speed of the ocean current but also the angle between the towed direction and the ocean current.

We think that the present research would surely be applicable to the estimation of the streamer behavior when towed in deep water and can be extendable to the problem of positioning.

I. Introduction

Recently, the development of new energy resources in deep water is of interest with much attention in the world, especially such as sea-floor hydrothermal deposit, because of the growth of world-wide requirement of metals. Hydrothermal deposits are found thinly and widely near the region of tectonically or volcanically active seafloor and are thought as the origin of black or pyritic ore deposits [1]. Since hydrothermal deposits are composed of sulfides with metal resources, it is very important to reveal the distribution of hydrothermal deposit in order to plan the development of such

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project properly. In resource engineering, seismic survey has been used to explore natural resources on the strength of its ability in high resolution. However, to obtain the seismic section and the velocity profiles of bearing zones of hydrothermal deposit with adequate resolution, high frequency deep-towed seismic survey whose feature is that both the seismic source and the streamer cable are towed closely to the seabed is needed. The short distance between the seismic source and candidate will give us high resolution data. So we focus attention on the "Deep-Towed Acoustic/Geophysics System (DTAGS)", developed by the Naval Research Laboratory, USA [2]. Both the source and the receivers are towed close to the seabed, allowing a "close look" at the shallow sediments (Fig.1).

One of the problems of the deep-towed seismic survey is a cable feathering phenomenon which is the curvature of the towed streamer cable in the ocean current [3] [4]. This problem leads less-accurate results in data processing phase due to the positioning error of the receivers [5]. So, it is useful to evaluate the degree of positioning error in advance. Especially, in case of strong current, the drag force estimation is also very important evaluation item.

Numerical simulation is a very efficient tool to predict the cable behavior in the ocean current [6]. In case of the streamer cable is towed in the deep sea, the streamer cable will wave due to the ocean current and the force of towing. At the same time, the deformed streamer cable will also influence the ocean current in the vicinity of the cable. This phenomenon that includes both fluid flow and the structural deformation is one of the Fluid – Structure – Interaction (FSI) problems. In numerical simulation of this type problem, the satisfaction of the geometrical compatibility and the equilibrium conditions on the interface is a key issue. Since strong dependence between the cable behavior and ocean current is expected, we adopt strong coupling method which is effective for the FSI problems with strong dependence between the structure and

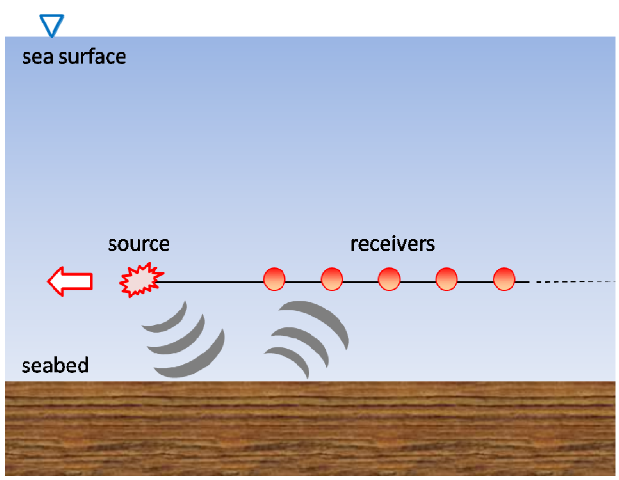


Figure 1. Deep-tow seismic data acquisition system. Both the source and the receivers are towed close to the seabed.

fluid flow [7]. In this study, arbitrary Lagrangian - Eulerian (ALE) finite element formulation is employed for the fluid domain, and total Lagrangian formulation for the cable. The geometrical compatibility conditions and the equilibrium conditions on the interface are automatically established by equating the displacement, velocity and acceleration on the interface common to the fluid and the cable. By using this method, the accurate numerical simulations of the cable behavior are expected.

In this research, we conduct some numerical simulations with different numerical parameters to evaluate the effect of the speed of the ocean current and the angle between the towed streamer cable and the ocean current on the cable feathering phenomenon and the drag force. Numerical model with different speed of the ocean current (0.5, 1, 2m/s), different angle between the towed streamer cable and the ocean current (0, 30, 60, 90 degrees) are numerically analyzed.

II. COMPUTATIONAL METHOD

The fluid-structure coupling method plays a key role in ensuring the accuracy and stability of the computation. In order to achieve accurate representations of the moving interfaces, we use the fluid-structure strongly-coupled finite element method with ALE mesh technique.

We assume the behavior of the ocean current to be governed by the incompressible Navier-Stokes equations. The ALE form of the governing equations is given as follows:

$$\rho_f\{\partial \mathbf{v}(\boldsymbol{\chi}, t)/\partial t + \mathbf{c}\cdot\nabla_x \mathbf{v}\} = \nabla_x \mathbf{T} + \rho_f \mathbf{b} \quad (1)$$

$$\nabla_x \cdot \mathbf{v} = 0 \quad (2)$$

where $\mathbf{v}$ is the flow velocities of the ocean current, t is the present time, $\mathbf{c}$ is the ALE convective velocities, $\mathbf{T}$ is the Cauchy stress tensor. χ and x are the ALE and the spatial coordinates, respectively.

On the other hand, the equilibrium equation of the structure is described in the total Lagrangian form as follows:

$$\rho_s\{\partial^2 \mathbf{u}(\mathbf{X}, t)/\partial t^2\} = \nabla_X(\mathbf{S}\cdot\mathbf{F}^T) + \rho_s \mathbf{b} \quad (3)$$

where $\mathbf{u}$ is the displacement of the structure, $\mathbf{F}$ is the deformation gradient tensor, $\mathbf{S}$ is the second Piola-Kirchhoff stress tensor.

On the fluid-structure interfaces, the following geometrical and mechanical conditions must be satisfied:

$$\mathbf{v}(\boldsymbol{\chi}, t) = \partial \mathbf{u}(\mathbf{X}, t)/\partial t \quad (4)$$

$$\mathbf{t}_f + \mathbf{t}_s = 0 \quad (5)$$

$\mathbf{t}_f$ and $\mathbf{t}_s$ are the traction force vectors of fluid and structure on the interface, respectively. These conditions are satisfied by simply defining the same nodes and shape function for the fluid and the structure on the interface.

The discretized equations for the fluid-structure coupling system can be expressed as follows by applying the virtual power principle to the whole domain.

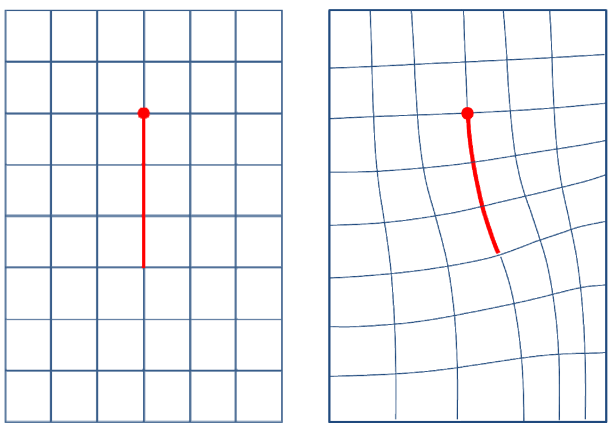
$$\mathbf{M} \cdot \mathbf{a}_{t+\Delta t} + \mathbf{C} \cdot \mathbf{v}_{t+\Delta t} + \mathbf{K} \cdot \mathbf{d}_{t+\Delta t} = \mathbf{F}_{t+\Delta t} \qquad (6)$$

M is the mass matrix compose of those for the fluid and the structure, **C** consists of the divergence, viscous and convective terms of the fluid, **K** is the tangent stiffness matrix of the structure. **F** is the external force vector. **a**, **v**, **d** are the generalized acceleration, velocity and displacement vectors of the coupled system, respectively. Eq. (6) is solved implicitly as a single system with Newmark-β method.

In present study, the fluid mesh moves to track the Lagrangian nodes of the structure as shown in Fig.2. The other ALE nodes are controlled to follow the moving interfaces by solving linear elasticity equations as the cable displacement is a fundamental boundary condition. The ALE convective velocity $\mathbf{c}$ in Eq.(1) is calculated by using the velocity of the moving meshes $\hat{\mathbf{v}}$ as follows:

$$\mathbf{c} = \mathbf{v} - \hat{\mathbf{v}} \qquad (7)$$

The Young's modulus of fluid element is in inverse proportion to its area to keep healthy mesh.



(a) (b)

Figure 2. The conceptual diagram of the fluid mesh movement. The red line and the blue squares represent the streamer cable and the finite element meshes for fluid domain, respectively.
(a) Before deformation. (b) After deformation.

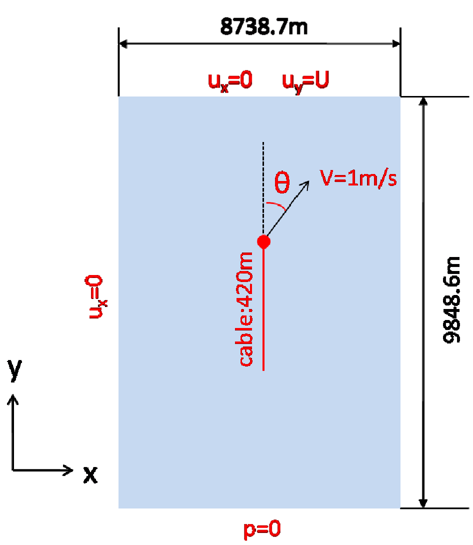


Figure 3. Schematic figure of the simulation model.

III. SIMULATION RESULTS

A. Model Descriptions

The schematic figure of the numerical model used in the present study is shown in Fig.3. 8738.7m×9848.6m area is modeled. The cable is aligned in y-direction and dragged against the ocean current with a certain angle. A red line in Fig.3 represents the cable. A red filled circle represents the top of the cable and imposed known drag speed as a fundamental boundary condition. The velocity of the ocean current "U" and the angle between the towed streamer cable and the ocean current "θ" listed in Table 1 are changed in each numerical simulation. The side wall and the outflow boundary conditions are $u_x = 0$ and $p = 0$, respectively. The drag speed and the length of the cable are fixed as shown in Fig.3.

The movement of the cable induces complex flow of the ocean current which also induce the deformation of the cable. The ALE finite elements in fluid domain track this cable deformation as shown in Fig.2. In each investigation about the positioning error and the drag force, the result will be obtained after the cable is towed about 1000m.

In this study, we numerically analyze the cable feathering phenomenon as a two-dimensional model. For simplification and idealization, we assume that buoyancy and gravity forces can be ignored although source and receiver depth are also important for the accuracy of data process.

B. Positioning Errors

In conventional marine acquisition, the position of the vessel and the streamer cable can be determined with sufficient accuracy for the resolution of the data. However, it

Table 1. Parameters for the numerical simulations.

CASE	Ocean current "U" (m/s)	Angle "θ" (degrees)
case-1	0.5	0
case-2	0.5	30
case-3	0.5	60
case-4	0.5	90
case-5	1.0	0
case-6	1.0	30
case-7	1.0	60
case-8	1.0	90
case-9	2.0	0
case-10	2.0	30
case-11	2.0	60
case-12	2.0	90

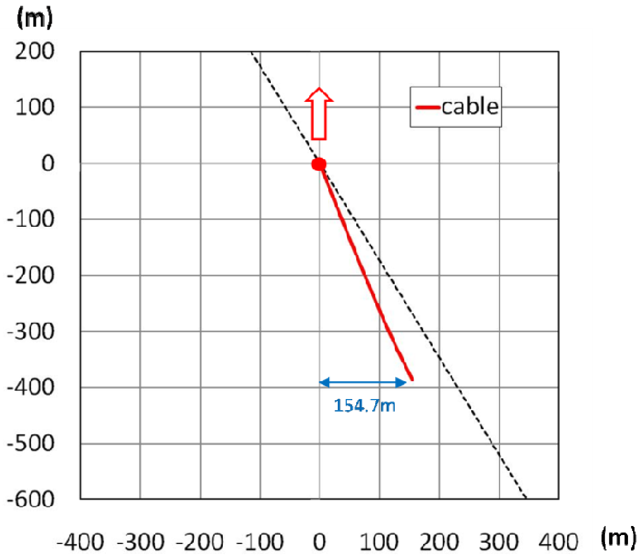


Figure 4. The cable feathering behavior in case-2.

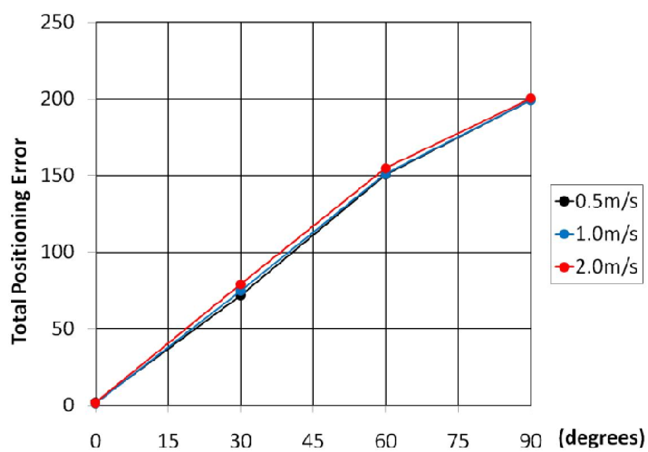


Figure 5. Total positioning error.

is difficult to determine the position of the source and the receivers for the deep-tow system, typically 1 km below the surface. So the accuracy of the positions of the source and the receivers is a key issue in the processing of the deep-tow data, it is very important to predict the possible positioning errors in practical marine area.

Fig.4 shows an example of the cable feathering phenomenon reproduced by the numerical simulation in case-2. The center of the graph "(x, y) = (0, 0)" represents the top of the cable, and vertical direction represents the cable towing direction indicated by red arrow. The ocean current comes from ahead of the cable on the left with 30 degrees. The solid red line and doted black line represent the cable and the ocean current direction, respectively.

As shown in Fig.4, the cable is flowed right side and approximately linear in the ocean current. However, the end of the cable is slightly flapped by the ocean current. This behavior causes the increase in the positioning error. Here, we define the positioning error as the distance between the cable and the axis of the towing direction. The estimated positioning error at the end of the cable is 154.7m in this case. This result shows the positioning error in practical marine area can be severe, considering that the cable length is 420m.

Next, we estimate the total positioning error in several cases. In this paper, the total positioning error is defined as follows:

$$\text{Total Positioning Error} = \sum_{i=1}^{n} P_i / n \qquad (8)$$

where n is the number of the nodes constitute the cable, P_i is the positioning error with respect to each node.

Fig.5 shows the total positioning error obtained by numerical simulations. The total positioning error increases approximately linearly with an increase in the angle between the towed streamer cable and the ocean current in each velocity of the ocean current. On the other hand, the velocity of the ocean current has less effect than the angle. This result indicates that the angle between the towed streamer cable and the ocean current is important for the positioning problem even if the speed of the ocean current is slow.

C. Drag Force

The drag force during towing the cable is numerically simulated. In case of strong current, the drag force estimation is also very important evaluation item. Fig.6 shows the simulation results of the cable drag force. The vertical axis in Fig.6 is the normalized drag force as a basis of the result in case-2. The drag force is calculated at a towing point.

As shown in Fig.6, the drag force increases with an increase in both the velocity of the ocean current and the angle between the towed streamer cable and the ocean current. In each velocity, the drag force in case of 90 degrees is about six times larger than that in case of 0 degree. The trend of the increment is not linearity but step-like pattern and the amount of increment from 30 degrees to 60 degrees is the largest.

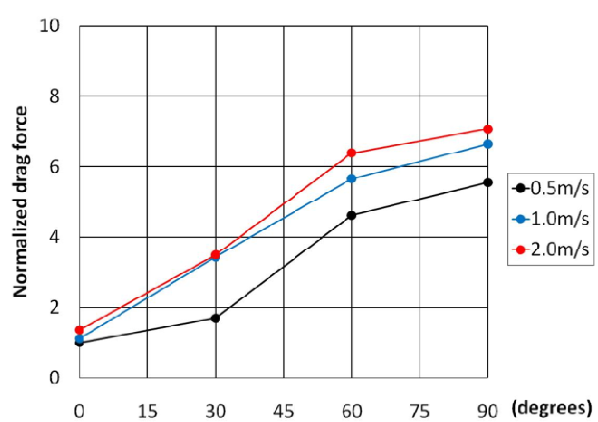


Figure 6. Normalized drag force.

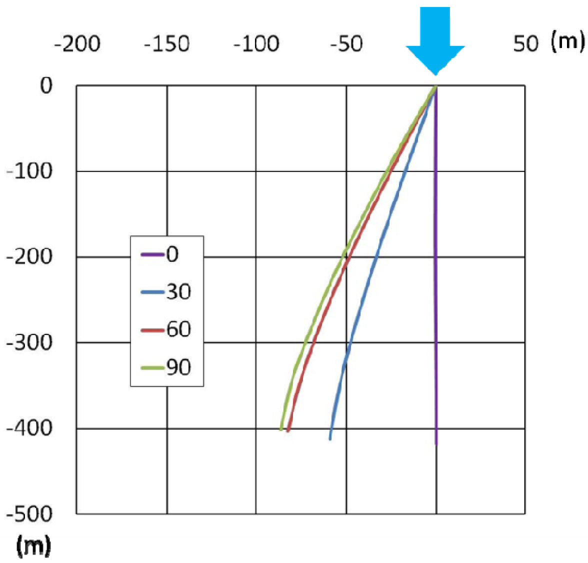


Figure 7. The cable behavior in case1-4.

Fig.7 shows the cable behavior in case1-4. The blue arrow placed the upper side of the horizontal axis represents the direction of the ocean current and four lines represent the cable behavior in different towing angle against the current direction. As shown in Fig.7, the cable is flowed in the ocean current with a certain angle. The flapping angle of the cable against the current direction increases with an increase in the towing angle. This will lead an increment of acting force from ocean current due to the curvature of the cable. This result indicates that the drag force as well as the positioning problem is influenced the angle between the towed streamer cable and the ocean current.

IV. CONCLUSIONS

In this paper, we conducted numerical simulations of cable feathering phenomenon in the ocean current. The interface tracking ALE finite element method with a strongly coupled formulation is used. Our numerical simulation successfully reproduced the cable feathering phenomenon that arises when the cable is towed. The effects of the current velocity, the orientation of the current against the towed streamer cable on the positioning error and drag force were investigated to estimate the order of the interference due to the towing.

The positioning error defined as the distance between the cable and the axis of the towing direction is severely influenced by the angle between the towed streamer cable and the ocean current. On the other hand, the velocity of the ocean current has less influence than the angle between the towed streamer cable and the ocean current. The total positioning error increases approximately linearly with an increase in the angle between the towed streamer cable and the ocean current.

The drag force at a towing point is also influenced by the angle between the towed streamer cable and the ocean current. The trend of the increment is not linearity but step-like pattern and the amount of increment from 30 degrees to 60 degrees is the largest.

Along with the development of acoustic positioning technologies may reduce the positioning error, we think that further studies on the behavior of cables would surely contribute to constrain the cable location and to minimize the location error that is unavoidable in the current practice of deep-towed surveys.

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