POAC'17
Busan, KOREA

Proceedings of the 24th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 11-16, 2017, Busan, Korea

Development of Platform Motion-Mooring System Coupled Solver for Offshore Plant

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ABSTRACT

Typically, the commercial softwares for the mooring system analysis are based on the potential flow theory for the analysis of the motion of platform and do not consider the viscous effects around the platform which affect the motion of it. To resolve this problem, in present study, we developed the model for the mooring system analysis with the lumped mass model and coupled it with the open source computational fluid dynamics libraries, OpenFOAM, which can simulate the motion of platform based on the viscous flow theory. Finally, the two-way coupled solver between six-degrees of freedom motion of platform and the tensile loads of the mooring system for offshore plant was developed and validated by comparing the calculation results with the analytic solution and experimental results, and its operability and robustness were confirmed by performing the calculation under various conditions of the platform motion.

KEY WORDS: Open source libraries; 6-DOF platform motion; Mooring system; Lumped mass model; 2-way coupling

INTRODUCTION

Global performance due to station keeping capability is one of the most important factors in the performance of offshore plant, which is determined entirely by the mooring system. Therefore, the mooring system design is essential to ensure the life and performance of the offshore plant. For this purpose, it is necessary to accurately predict the motion of the platform under the given environmental loads and the tensile load of the mooring system accordingly.

However, most commercial codes used for the analysis of mooring systems are based on the potential flow theory which doesn't consider the viscous effects around the platform in analyzing the motion of it, so it is difficult to predict the exact motion of the platform in the actual flow. Additionally, in analyzing the mooring system, a reasonable model is required to accurately predict the tensile load and the overall dynamic characteristics of the mooring line, and the consideration of bidirectional coupled analysis in which the motion of the platform and the tensile load of the mooring system are mutually influenced is also required.

This study was conducted as part of a project to develop a simulation suite for the analysis of polar environmental loads acting on the arctic ships and offshore plants, and the coupled solver between the platform motion and mooring system for offshore plant was developed. In order to analyze the platform motion and mooring system, an open source computational fluid dynamics (CFD) libraries, OpenFOAM, which can simulate the viscous flow analysis and the lumped mass mooring system model which can predict the accurate tensile load and dynamic characteristics of mooring lines were used, respectively.

LUMPED MASS MOORING SYSTEM MODEL

The quasi static model, which has low computation load, easy to use, and easy to apply to open source (Masciola et al., 2013), has been widely used as a model for mooring system analysis. However, since this model does not take into account the hydrodynamic forces and internal forces on the mooring line, there is a difficulty in accurately predicting the platform motion and the tensile load of the mooring system. Therefore, in this study, a lumped mass model which neglects the bending and torsional elasticity of the mooring line was used to reduce the computation load without affecting the calculation results (Hall et al., 2014).

The discretized mooring line is shown in Figure 1. The evenly divided segments have the identical properties, such as length (l), diameter (d), density (ρ), Young's modulus (E), and internal damping coefficient (C_{int}), and the nodes, i.e., lumped mass, have the integer indices then the vector r_i represents the position of node i. For the segments which are adjacent to node i, the indices $i\text{-}1/2$ and $i+1/2$ were used, respectively. Figure 2 shows internal and external forces acting on the discretized nodes and segments and theses forces are included in the equation of motion at each node (Hall and Goupee, 2015). The details of forces will be described in the following two subsections.

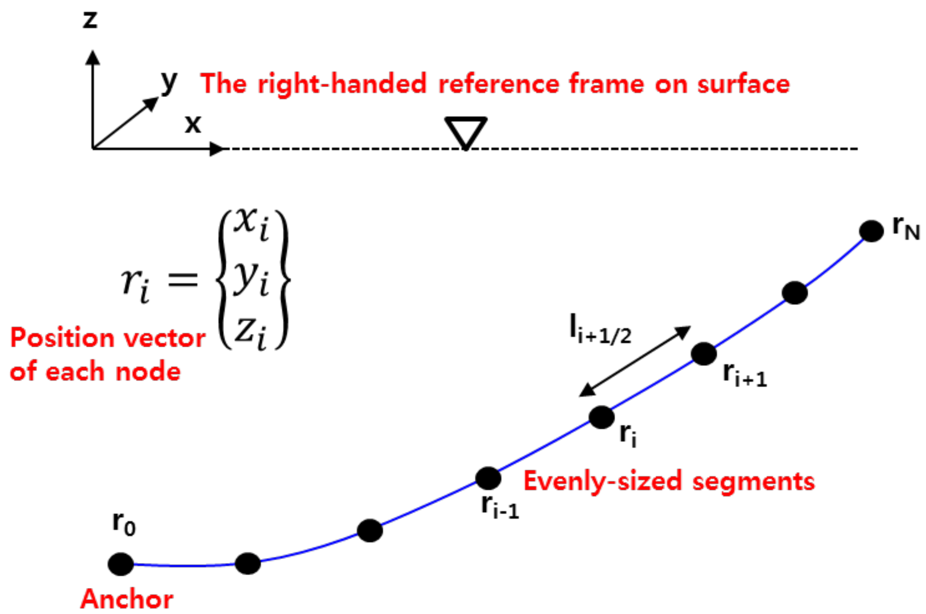

Figure 1. Discretized mooring line and indices

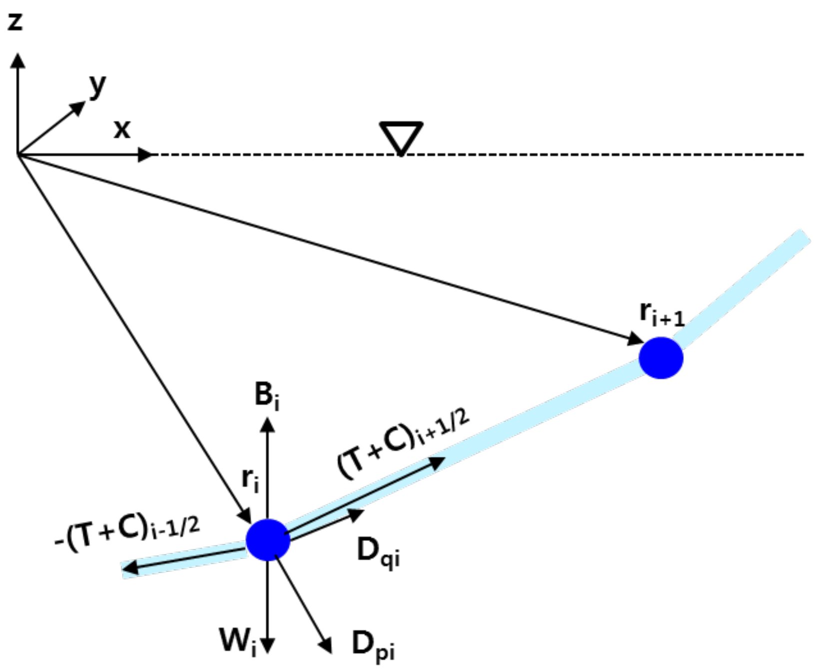

Figure 2. Internal and external forces acting on the nodes and segments

Internal Forces on the Mooring Line

The internal forces consist of axial stiffness (T), axial damping (C), and net buoyancy (W). Axial stiffness and damping are acting on the segments and calculated as

$$T_{i+1/2} = E\frac{\pi}{4}d^2\epsilon_{i+1/2} \tag{1}$$

$$C_{i+1/2} = C_{int}\frac{\pi}{4}d^2\dot{\epsilon}_{i+1/2} \tag{2}$$

where ϵ and $\dot{\epsilon}$ are the strain and strain rate, respectively.

Net buoyancy is acting on the nodes and calculated as

$$W_i = \frac{1}{2}\left[\left\{\frac{\pi}{4}d^2l(\rho_w-\rho)g\right\}_{i+1/2} - \left\{\frac{\pi}{4}d^2l(\rho_w-\rho)g\right\}_{i-1/2}\right]\hat{e}_z \tag{3}$$

where ρ_w is the density of water, g is the gravitational acceleration, and $\hat{e}_z$ is the unit vector in the direction of z-axis.

External Forces on the Mooring Line

The external forces consist of drag forces, added mass forces, and contact force with the seabed, and they are acting on the nodes. The hydrodynamic forces, such as drag forces and added mass forces, are calculated using Morison's equation, and the transverse drag force (D_p) and tangential drag force (D_q) at node i are calculated as

$$D_{p_i} = \frac{1}{2}\rho_w C_{dn} dl \|(\dot{r}_i \cdot \hat{q}_i)\hat{q}_i - \dot{r}_i\| [(\dot{r}_i \cdot \hat{q}_i)\hat{q}_i - \dot{r}_i] \tag{4}$$

$$D_{q_i} = \frac{1}{2}\rho_w C_{dt} \pi dl \|(-\dot{r}_i \cdot \hat{q}_i)\hat{q}_i\| [(-\dot{r}_i \cdot \hat{q}_i)\hat{q}_i] \tag{5}$$

where C_{dn} and C_{dt} are the transverse and tangential drag coefficients, $-\dot{r}_i$ is the relative water velocity due to the motion of nodes, and $\hat{q}_i$ is the tangential unit vector at the nodes.

The transverse added mass force (a_p) and tangential added mass force (a_q) at node i are calculated as

$$a_{p_i}\ddot{r}_i = \rho_w C_{an} \frac{\pi}{4} d^2 l [(\ddot{r}_i \cdot \hat{q}_i)\hat{q}_i - \ddot{r}_i] \tag{6}$$

$$a_{q_i}\ddot{r}_i = \rho_w C_{at} \frac{\pi}{4} d^2 l [(-\ddot{r}_i \cdot \hat{q}_i)\hat{q}_i] \tag{7}$$

where C_{an} and C_{at} are the transverse and tangential added mass coefficients, $-\ddot{r}_i$ is the relative water acceleration due to the motion of nodes.

Finally, the contact force with the seabed is modeled as a linear spring-damper system, and it works only when the node contacts the seabed, i.e., z_i is equal to or less than z_{bot}. The contact force is calculated as

$$B_i = dl[(z_{bot} - z_i)k_b - \dot{z}_i c_b]\hat{e}_z \tag{8}$$

where k_b is the stiffness per unit area of the seabed, c_b is the viscous damping per unit area, z_i and z_{bot} are the z-axis coordinates of the node and the seabed, and $\dot{z}_i$ is the velocity of the node in the direction of z-axis.

MOORING SYSTEM MODEL VALIDATIONS

In order to validate the developed mooring analysis model, two reference cases, i.e., analytical solution and experimental result, were calculated and compared.

Comparison with the Analytical Solution

The first validation case is the analytical solution of line tensions along a single catenary mooring line (Irvine, 1981). The cable properties used are 0.25 m in diameter, 7,000 kg/m^3 in density, 2×10^{11} N/m^2 in Young's modulus, 500 m in mooring line length, 325 m and 350 m in horizontal and vertical distances from anchor to fairlead, 292.8 N/m in net mooring line weight per unit length in the water. The calculated mooring line tensions at nine locations were compared with the analytical solution, and the results were listed in Table 1. The calculation result showed great agreement with the analytical solution within the range of 0.34 %.

Table 1. Comparison of the calculated mooring line tension with the analytical solution

Length from anchor [m]	Analytic solution [N]	Calculated result [N]	Error [%]
55.55	655,966	656,119	0.02
111.10	726,777	726,170	0.08
166.65	822,934	821,526	0.17
222.20	936,663	934,420	0.24
277.75	1,062,335	1,059,250	0.29
333.30	1,196,193	1,192,310	0.32
388.85	1,335,778	1,331,210	0.34
444.40	1,479,469	1,474,390	0.34
500.00	1,626,178	1,620,780	0.33

Comparison with the Experimental Result

The second validation case is the experimental result of node positions along a single catenary mooring line (Nakajima et al., 1982). The cable properties used are 0.599 cm in diameter, 2.15×10^6 kg/cm^2 in Young's modulus, 9 m in mooring line length, 8.42 m and 3 m in horizontal and vertical distances from anchor to fairlead, 0.1938 kg/m in net mooring line weight per unit length in the water. The calculated mooring line node positions were compared with the experimental result at five points because the reference gives information of only those points. The results were listed in Table 2, and they showed good agreement with the experimental results.

Table 2. Comparison of the calculated mooring line positions with the experimental results

	X-exp [m]	X-cal [m]	X-err [%]	Y-exp [m]	Y-cal [m]	Y-err [%]
Anchor	0.00	0.00	-	0.00	0.00	-
Node 3	3.0021154	2.99761	0.15	0.3605167	0.37579	4.23
Node 6	5.8431810	5.83557	0.13	1.4093504	1.4205	0.79
Node 8	7.6015360	7.58936	0.16	2.4063136	2.423265	0.70
Fairlead	8.42	8.42	-	3.00	3.00	-

COUPLING WITH THE PLATFORM MOTIONS

The developed mooring system analysis model consists of three modules to couple with the platform motion. The first is a module that sets the initial conditions based on the shape of a mooring system and the properties of the mooring line and calculates initial values when the time is zero seconds and is called the initialization module. The second is a module that calculates the tensile load of the mooring system by receiving the information of platform motion such as current time, time step size, position, and velocity as the time progresses and is called the calculation module. The last is a module that frees the variables and memories which were used to calculate the tensile load of the mooring system after the end of calculations and is called the termination module.

After three modules, i.e. functions, that mentioned above are compiled into a single shared library file, the modules can be called as a form of function into the code that generates or analyses the platform motion by the dynamic loading (Beazley et al., 2001), as shown in 3, then the coupling between the mooring system analysis model and the platform motion is completed. Figure 4 shows the calculation procedure. When it starts, the mooring system analysis model gets the initial information of platform motion and calculates the initial tensile load and the mooring system profile until the fairlead tension is converged. Then the platform motion solver goes one time step forward, and the mooring system analysis model repeats receiving the information of platform motion and calculating the tensile load and the mooring system profile at each time step until the platform motion is no more updated.

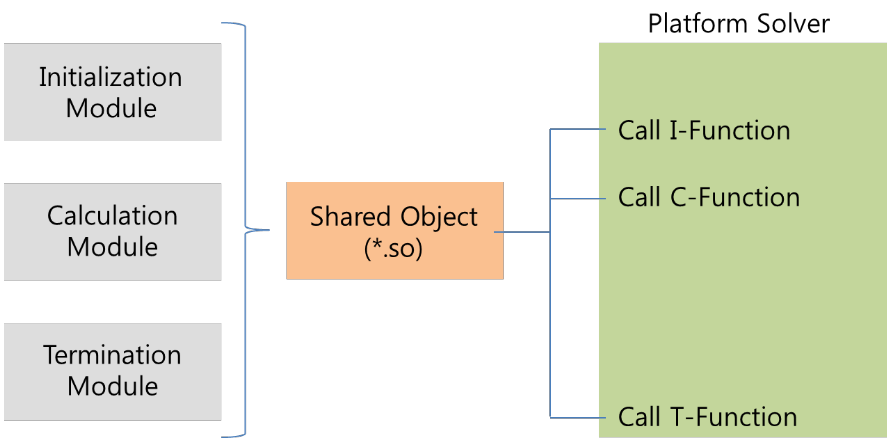

Figure 3. Shared library and dynamic loading of functions

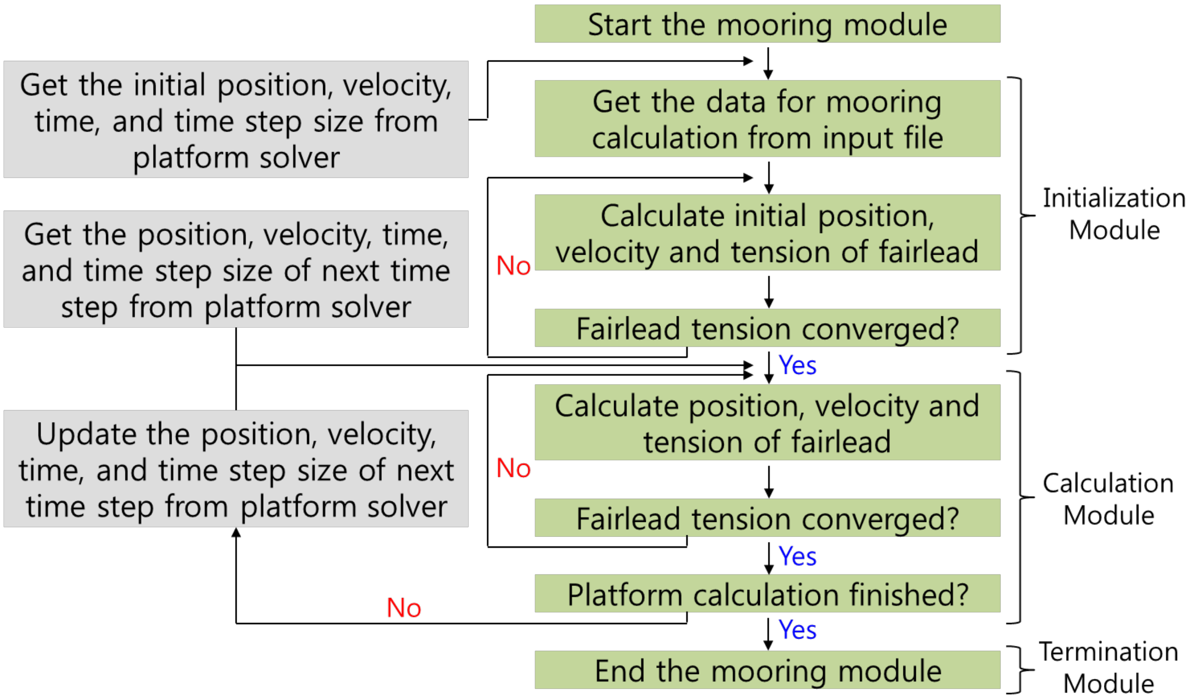

Figure 4. Calculation procedure of the mooring system analysis model

Platform Motion in the Calm Water

Simple calculation was performed to verify that the coupling between the platform behavior and the mooring analysis model through shared library files and dynamic loading works well. In this case, the tensile loads of the mooring system were calculated for a simple platform motion in the calm water. The identical three mooring lines which have arbitrary properties are connected to the SPAR-shaped platform at 120-degree intervals, as shown in Fig. 5, and the platform was set to move at a constant velocity in x-axis direction.

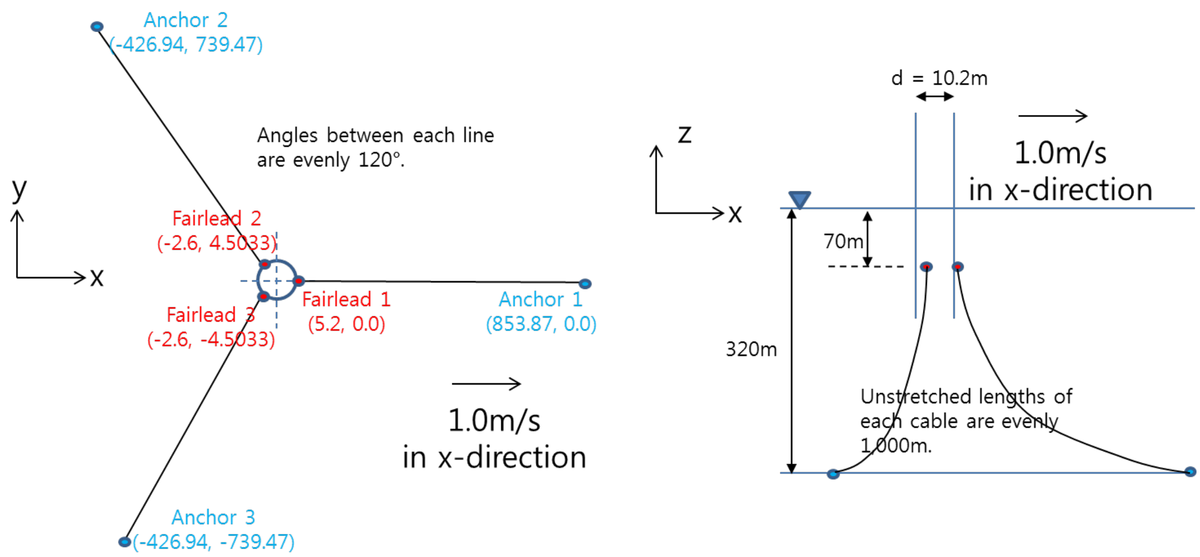

Figure 5. Schematic of the mooring system and the platform motion

Figure 6 shows the calculated tensile loads with the constant velocity in the calm water. The tensile load on the fairlead 1 which was connected to the direction of movement of the platform gradually decreased, while the tensile loads on the fairleads 2 and 3 connected in the opposite direction gradually increased. In addition, since the mooring lines connected to the fairleads 2 and 3 are symmetrical about the x-axis, the tensile loads acting on the fairleads 2 and 3 are identical. These are all physically reasonable results and show that the coupling between the platform motion and the mooring system analysis model works properly.

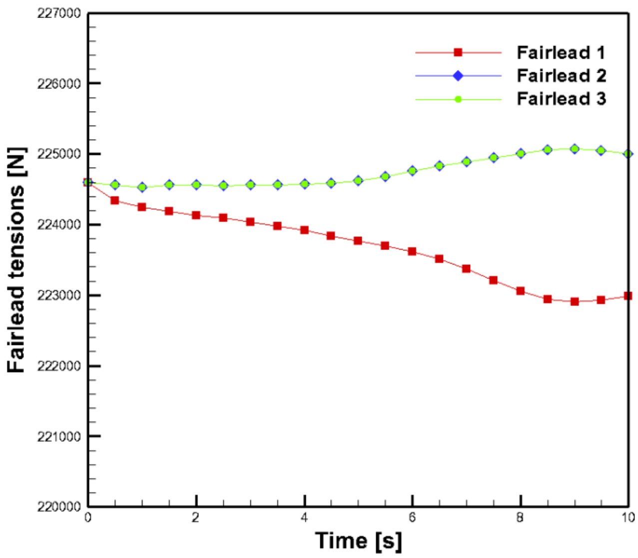

Figure 6. Calculated tensile loads with the constant velocity platform motion in the calm water

Ice Impact Load on the Platform

Another calculation was performed to confirm that the mooring system analysis model works robustly when the impact load, such as a collision with ice or ship, are applied to the platform. In this case, based on the same platform and mooring system as the previous case, the platform was stationary in the calm water at the initial period, then the impact load in the x-axis direction gave a sudden acceleration change to the platform during the short time interval and generated the motion of it, and the platform motion was decaying as time goes by.

Figure 7 shows the calculated tensile loads under the impact load acting on the stationary platform in the calm water. Initially, there is no motion of the platform, so the tensile loads acting on the three fairleads are all the same. When the impact load is applied to the platform after a short time, it can be seen that the tensile load shows the rapid change with a peak and it is stabilized after the external force was disappeared. After that, the tensile loads were increased or decreased with the general tendency by the residual motion. These results show that the developed mooring system analysis model can work robustly under the impact loading conditions, and can capture the abrupt change in the platform motion due to the external force to reflect it in the tensile load calculation.

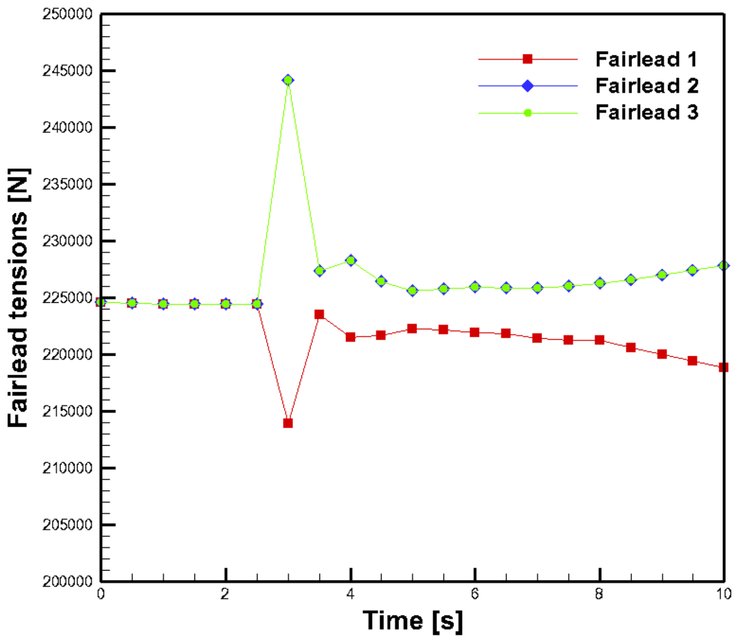

Figure 7. Calculated tensile loads under ice impact load on the stationary platform in the calm water

CONCLUSIONS

The mooring system analysis model based on the lumped mass model was developed to calculate the tensile load of the mooring system as a part of a project to develop a simulation suite for the analysis of polar environmental loads acting on the arctic ships and offshore plants, and the internal forces, such as net buoyancy, internal stiffness, and internal damping, and the external forces, such as drag forces, added mass forces, and contact force with the seabed, were included in it. The validation results of the tensile loads showed very good agreements with the analytical solution and the experimental results.

The developed mooring system analysis model was divided into three modules or functions to couple with the platform motion easily, and was coupled via dynamic loading of shared library. The coupled analyses were performed to confirm its operability and robustness for the cases of platform motion in the calm water, impact load on the platform, and coupling with the open source CFD solver, and it showed good performance and qualitatively reasonable results.

Future studies will be conducted to verify the platform motion and the tensile load of the mooring in the regular and irregular waves with an ice impact load.

ACKNOWLEDGEMENTS

Our research was supported by the National Research Foundation (2015037577) and the IT R&D Program of MOTIE/KEIT (10060329) funded by the Korea government.

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