Mooring system design for an underwater floating tidal current power device

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Abstract— **Support structures for tidal current power (TCP) generators can be divided into self-weight embedment, fixed-pile, and mooring types. Mooring-type TCP systems use buoyancy and mooring lines to stay afloat. Mooring-type support structures can be installed in any depth of water, so the installation process is simple, and costs can be significantly reduced. However, compared to other types of support structures, the motion of mooring structures is relatively large and requires an optimal system design to maximize power generation and secure dynamic motion stability. In this study, an optimal design is suggested for the mooring system of a floating TCP system using OrcaFlex 10.1a, a time-domain analysis program. The mooring system was developed by considering the sea environment and meets the design criteria for a wave energy converter (WEC) and TCP. Its pitch motion and yaw motion were maintained within approximately 3°. The results of this study could be used as basic information for the application of underwater floating TCP systems in various sea conditions.**

Keywords— **Underwater floating, tidal current, hydrodynamic coefficient, response amplitude, mooring system**

I. INTRODUCTION

Tidal current is a reliable source of energy with a high energy density and can continuously generate power regardless of weather or seasonal conditions. The amount of power can be predicted precisely compared to other renewable energy sources. The western and southern seas in Korea are known to have some of the highest energy reserves in the world thanks to geographical features such as narrow channels between numerous islands [1].

Studies conducted on tidal current power (TCP) in Korea mostly focus on fixed-pile [2] or self-weight embedment generators that use caisson structures [3]. However, these support structures result in significant costs in production and installation, and they cannot be installed in deep waters, so their applicability is limited. Recently, studies have been actively conducted on TCP systems using mooring support systems to address these constraints. Mooring support systems can reduce the costs of the installation and structures compared to the other support structures. They can also be installed and uninstalled easily for production and maintenance, and they have fewer constraints related to the depth of water.

Jo et al. [4] developed a submerged single-point mooring TCP system using only turbines and ducts. They analysed the motion performance using numerical and modelling analyses. PLAT-O#2 is a 200-kW TCP generator that was developed in the United Kingdom that supports a submerged platform equipped with four turbines using mooring structures. Its 6-DOF motion performance and the tension of the mooring lines were compared using numerical analysis and experiments [5].

To secure the stability of ocean platforms that have mooring support structures, it is important to review the dynamic response of ocean platforms and the dynamic load of mooring lines. Kim and McEvoy explored the stress-strain response and motion of a floating tidal device using a non-linear polymer mooring line [6]. Kim et al. [7] researched effective arrangements of mooring lines by analysing the frequency and time responses of combined renewable energy platforms. They examined the safety of mooring lines through a fatigue analysis.

In this study, a mooring system was developed using a split plate to minimize the pitch motion responses, which can significantly affect the power generation. The dynamic responses of an underwater TCP system with different mooring systems and the tension of mooring lines were analysed to optimize the design. A numerical analysis was performed using the commercial program OrcaFlex 10.1a, and an optimal mooring system design was developed by considering the responses with different hang-off angles, azimuth angles, fairlead points, and locations of the split plate. In addition, the 6-DOF dynamic responses in the design environment, the safety coefficient of the mooring lines in an extreme environment, and the occurrence of line clashes were examined to assess the safety of the system.

II. 4-POINT SINGLE-LINE MOORING SYSTEM

A. *Analysis model and specifications*

Table 1 and Fig. 1 show the shapes and specifications of the analysis model of the underwater floating TCP system. The system includes a duct that accelerates the flow velocity and a buoyant body that can control the buoyancy using seawater pumps. It also has a strut that controls the yaw rate by changing the direction of the tidal current and a horizontal-axis turbine. To consider the dynamic effects of the turbines, the thrust coefficient and moment were set as 0.96 and 1.176 kN.m, respectively, and the buoyancy ratio of the total system was set as 1.7.

A 4-point tension mooring system was applied to support the floating TCP system. The mooring lines are 20-mm 6x19 IWRC wire ropes, and their allowable load is 252.1 kN. The key specifications of the mooring lines are shown in Table 2.

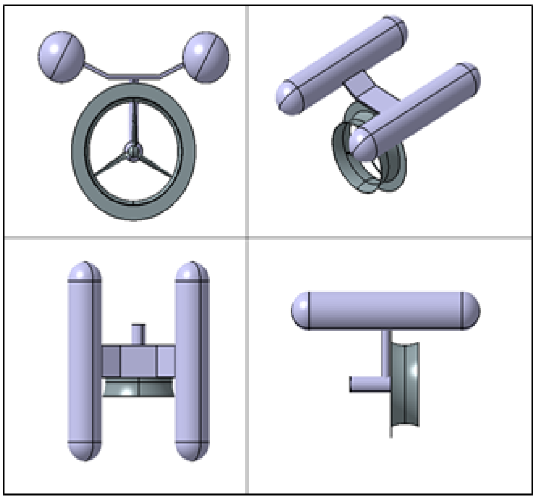

Fig. 1 Model of floating TCP

TABLE I
PRINCIPAL DIMENSIONS OF FLOATING TCP

Description	**Value**
Length [m]	7.4
Width [m]	4.42
Height [m]	3.2
Buoy diameter [m]	1.4
Turbine diameter [m]	3.7
Turbine thrust coefficient	0.96
Turbine moment [kN·m]	1.176
Total weight [kg]	5,306
Total buoyancy [kg]	23,085
Ballast water [kg]	13,579

B. Analysis conditions and variables

The modelling and analysis conditions for OrcaFlex 10.1a are shown in Fig. 2 and Table 3. The wave load was based on the marine environment of Uldolmok, a channel located near Jindo Island, and the significant wave height and peak wave period were set as 1.1 m and 3.6 s, respectively [3]. The TMA spectrum was applied to create shallow sea conditions and a coastal environment similar to those of Korea. The TMA spectrum is known as the most suitable frequency spectrum for this coastal environment. The current load was set as 1.5 m/s, which is the design flow velocity of tidal current turbines. The environmental forces were assumed to be applied vertically to the turbines to assess the stability of the mooring lines under the operation conditions.

TABLE II
MECHANICAL PROPERTIES OF MOORING LINE

Description	**Value**
Diameter [mm]	20
(6X19 IWRC wire rope)	
Mass in air [kg/m]	1.6
Breaking load [kN]	252.1
Axial stiffness [kN]	16,160

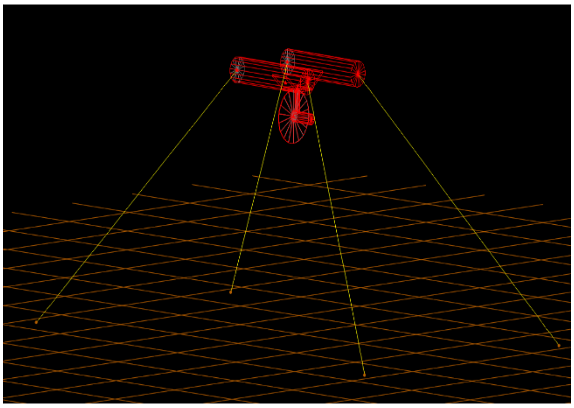

Fig. 2 OrcaFlex 10.1a model

TABLE III
ENVIRONMENTAL CONDITION

Description	**Value**
Significant wave height (H_s) [m]	1.1
Peak period (T_P) [s]	3.6
Wave type	TMA spectrum
Current speed [m/s]	1/7 Power law (1.5m/s at turbine)
Environmental force direction	Perpendicular
Water depth [m]	-20
Location [m]	-10

To develop an optimal design, as shown in Fig. 3 and Table 4, the hang-off angle, azimuth angle, and fairlead point of the mooring lines were used as analysis parameters. The maximum hang-off angle was set as 64° by considering the actual installation area (50X50 m^2). The azimuth angle was set as 30° by considering the radial angle (45°) of the 4-point mooring lines and the distribution of the tidal current directions. The maximum fairlead point was set as 1 m by considering the interference between turbines.

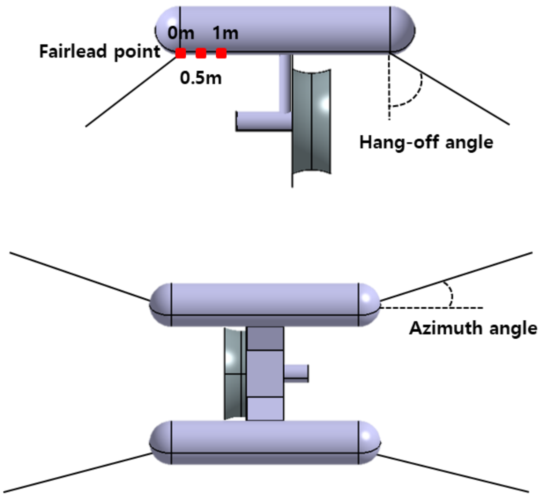

Fig. 3 Key parameter definitions for analysis

TABLE IV
KEY PARAMETERS FOR ANALYSIS

Description	**Value**
Hang-off angle [deg.]	50-64°, 2° intervals
Azimuth angle [deg.]	30°, 45°
Fairlead point [m]	0 m, 0.5 m, 1 m

C. Analysis results

Fig. 4 and 5 show the pitch motion responses in the time domain and the maximum loads of the mooring lines according to the hang-off angle. Higher hang-off angle and tension of the mooring lines suppress the motion responses of the floating TCP system and reduce the pitch motion responses. In addition, as the azimuth angle and fairlead point decrease, the pitch motions also tend to decrease. Based on the analysis results, the optimal conditions for a single-line mooring system were obtained as follows: hang-off angle: 64°; azimuth angle: 30°; fairlead point: 0 m. Under these conditions, the maximum pitch response is 5.33°.

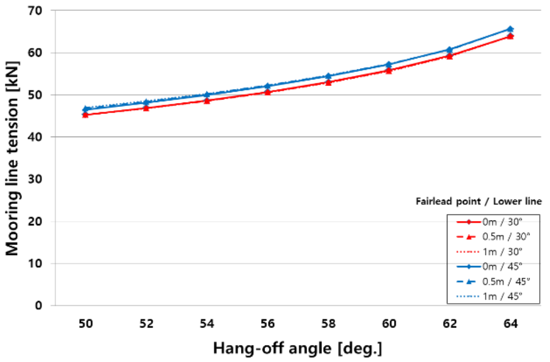

Fig. 4 Time domain pitch response with parameters

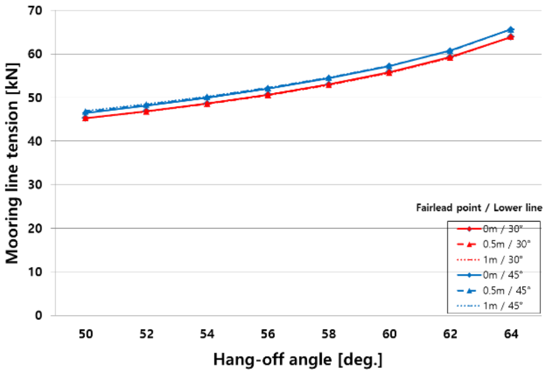

Fig. 5 Time-domain mooring tension with parameters

III. MOORING SYSTEM USING SPLIT PLATE

A. Analysis conditions and variables

A mooring system that can distribute mooring lines using a split plate was developed to improve the pitch motion responses of the 4-point single-line mooring system, as shown in Fig. 6. Based on the optimal conditions obtained from the analysis results of the system, an optimal mooring system design was developed using a split plate. To do so, the fairlead point and the lengths of the upper line and lower line were changed, and the pitch motion responses were analysed. The fairlead point was set as 0, 0.5, and 1 m, which are the same as those of the 4-point single-line mooring system. The length of the lower line was set as 2, 3, 4, and 5 m. The length of the upper line was set differently to prevent any line clashes in each condition.

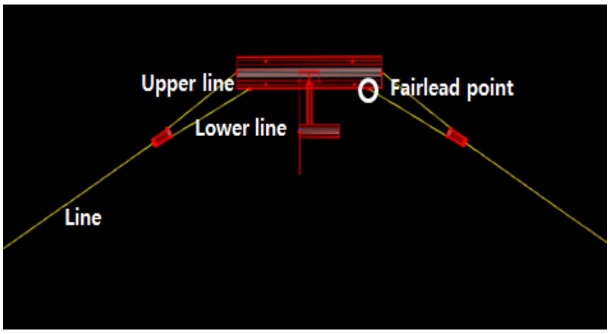

Fig. 6 Key parameter definitions for analysis using split plate

B. Analysis results

The analysis results show that a higher the fairlead point results in a lower pitch motion. The lowest pitch motion response (2.83°) was observed when the length of the lower line was 4 m and the length of the upper line was 3.2 m. By applying a split plate, the pitch motion response was improved by approximately 53.3% compared to the 4-point single-line mooring system.

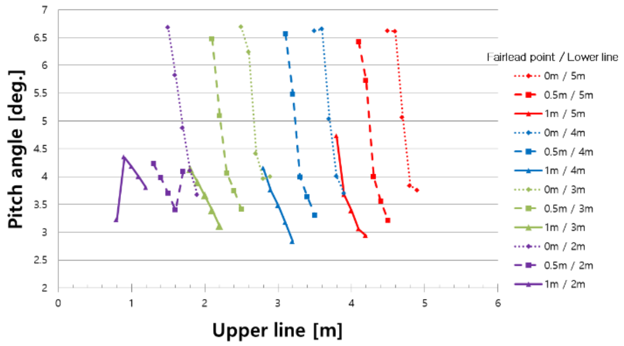

Fig. 7 Time-domain dynamic pitch response with parameters

IV. STABILITY IN AN EXTREME ENVIRONMENT

A. Definition of extreme marine environment

The IEC 62600-10 standard for designing floating TCP devices suggests considering the 50-year cycle of the marine environment when assessing the stability of a mooring-type TCP system. Therefore, the 50-year cycle was considered to assess the stability of the optimal mooring system. The extreme environment was defined as follows: flow velocity: 3.1 m/s; significant wave height: 1.6 m; peak wave period: 4.4s. In addition, the safety coefficient of the mooring lines and the occurrence of line clash were examined under the weakest conditions, in which environmental forces are applied to the mooring lines in parallel. Table 5 and Fig. 8 show the environmental forces and directions of the 50-year cycle.

TABLE V
ENVIRONMENTAL SURVIVAL CONDITIONS (50-YEAR CYCLE)

Survival conditions	
Current [m/s]	3.1
Significant wave height [m]	1.6
Peak period [s]	4.4

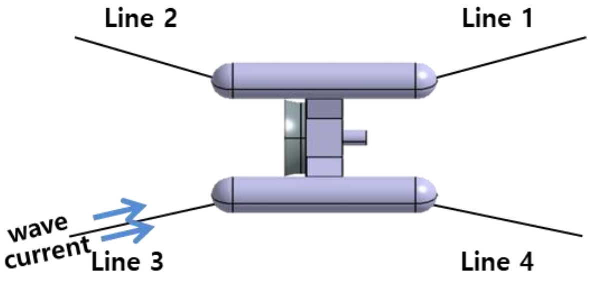

Fig. 8 Definition of direction of environmental force

B. Assessment of the safety coefficient of mooring lines

The maximum tension (140.1 kN) was observed in the mooring line in the direction in which environmental forces were applied. Considering the allowable load (252.1 kN) of the 20-mm wire rope used for the mooring lines, the safety coefficient was 1.79, which is similar to the safety coefficient (1.67) suggested in IEC 62600-10.

C. Occurrence of line clash

To examine the occurrence of line clash between mooring lines in the extreme marine environment, the minimum clearance distance was measured between the lower and upper lines at every point of every line. As shown in Table 6, the minimum clearance distance was found to be 0.15 m, which indicates that there was no line clash.

TABLE VI
LINE CLEARANCE FOR LOWER LINE

Arc Length [m]	**Line 1**	**Line 2**	**Line 3**	**Line 4**
0	1.39	1.25	1.19	1.25
0.1	1.32	1.18	1.09	1.17
0.3	1.26	1.06	0.95	1.09
0.5	1.19	0.94	0.83	1.00
0.7	1.12	0.81	0.72	0.92
0.9	1.05	0.69	0.63	0.83
1.1	0.99	0.59	0.55	0.75
1.3	0.92	0.50	0.48	0.67
1.4	0.85	0.42	0.42	0.59
1.6	0.78	0.35	0.35	0.51
1.8	0.72	0.30	0.26	0.45
2	0.65	0.26	0.19	0.39
2.2	0.59	0.25	0.15	0.34
2.4	0.53	0.25	0.15	0.32
2.6	0.48	0.26	0.16	0.32
2.8	0.41	0.29	0.23	0.32
3	0.39	0.32	0.31	0.35
3.1	0.39	0.36	0.40	0.37

V. CONCLUSIONS

This study analysed the changes in motion responses and tension with various parameters to develop an optimal mooring system design for an underwater floating TCP system. The analysis results of the mooring system with a single 4-point mooring line showed that the pitch motion responses surpassed the design limits. To address the issue, a mooring system was developed using a split plate. The optimal design was developed based on the motion stability in the design environment.

To assess the stability of the optimal mooring system, the safety coefficient of the mooring lines and the occurrence of line clash in the extreme environment were examined. The maximum pitch motion response of the optimal system in the design environment was 2.83°, and the safety coefficient of the mooring lines in the extreme environment was 1.79. The minimum clearance distance between mooring lines was 0.15 m. The developed system was found to be stable.

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REFERENCES

[1] D. S. Byun, D. E. Hart, & W. J. Jeong, “Tidal current energy resources off the South and West coasts of Korea: Preliminary observation-derived estimates.” Energies, 6(2), 566-578. 2013.

[2] C. H. Jo, D. Y. Kim, Y. H. Rho, K. H. Lee, & C. Johnstone, FSI analysis of deformation along offshore pile structure for tidal current power. Renewable energy, 54, 248-252. 2013.

[3] K. O. Ko, K. H. Lee, C. B. Park & C. H. Jo, “Design of Supporting Structure for Tidal Current Power Generation using Tidal Bladed”. Journal of Coastal Disaster Prevention, vol. 3, 113-127. 2016.

[4] C. H. Jo, H. J. Park, B. K. Cho & M. J. Kim, “Investigation of Motion of single Point Moored Duct-type TCP System by Both Numerical and Experimental Method.” Trans. of Korean Hydrogen and New Energy Society, 28(2), 212-219. 2017.

[5] I. Bivol, P. Jeffcoate, L. Johanning & R. Nicoll, “PLAT-O# 2 at FloWave: A tank-scale validation of ProteusDS dynamic analysis tool for floating tidal “ in proc. EWTEC, 2017.

[6] P. McEvoy, S.J. Kim, “Mooring load management for SR2000 floating tidal device using non-linear polymer components” in proc. EWTEC, 2017

[7] J. M. Choung, G. Y. Jeon & Y. I. Kim, Study on Effective Arrangement of Mooring Lines of Floating-type Combined Renewable Energy Platform. Journal of Ocean Engineering and Technology, 27(4), 22-32. 2013.