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Mooring Analysis of Duct-Type Tidal Current Power System in Shallow Water

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***Abstract*—**The exhaustion of oil and the environmental pollution from the use of fossil fuel are increasing. Tidal current power (TCP) has been proposed as an alternative energy source because of its predictability and reliability. By applying a duct and single point mooring (SPM) system, a TCP device can amplify the generating power and keep its position properly. Because the generating power is proportional to cube of the current stream velocity, amplifying the current speed by applying a duct to a TCP system is an effective way to improve the efficiency of the power device. An SPM system can be applied at any water depth and is highly cost effective. Simple installation and maintenance procedures are also merits of an SPM system. In this study, we designed an SPM system for a duct-type TCP device for use in shallow water. Motions of the duct are investigated to obtain the response amplitude operator (RAO) as the magnitude of the transfer function. Parameters affecting the stability of the SPM system such as the fairlead departure angle, current velocity, and the number of clamp weights are analyzed and/or optimized. Wadam and OrcaFlex commercial software is used to design the mooring line.

***Keywords*—**Mooring design, parametric analysis, response amplitude operator, single point mooring.

I. Introduction

TIDAL current energy is an important alternative clean energy source that will help solve the energy problem and reduce environmental disruption. Unlike other renewable sources, tidal current energy is very predictable and reliable. By converting kinetic energy into turbine rotational energy, a TCP system generates electricity. TCP has great potential throughout the world. As a result of these advantages, TCP systems have been the focus of extensive research.

Numerous studies have been presented regarding the upstream duct in TCP systems. Jo et al. conducted an experimental study on a ducted horizontal axis turbine (HAT) system [1]. The effects of the diffuser angle on ducted tidal turbine performance were presented by Khunthongjan et al. [2]. Kim et al. conducted computational fluid dynamics (CFD) analyses of the effects of inlet shapes on the inside velocity of the duct [3]. Luquet et al. introduced a duct system using hydrofoil sections around a turbine [4].

A strong current is required for tidal converters. Usually, TCP can generate electricity efficiently in regions with currents above 1 m/s. Since the upstream duct can accelerate the flow speed, it can potentially expand the applicable areas of tidal devices into relatively low velocity sites. In many studies, it has been proven that a duct can enhance the amount of power production by amplifying the flow velocity, but the duct should be designed by considering the specific environmental conditions and the type of TCP structure. In previous, a streamline-shaped duct was designed for a TCP system [5]. A duct having a streamline-shaped surface induces turbulence at the end of the duct, intensifies the suction effect that creates a pressure drop at the outlet of the duct, and amplifies the current's velocity. In the present study, a pre-designed streamline-shaped duct was adopted for use in a TCP system.

A mooring system exerts restoring forces and moments on a floating structure, thereby pulling the structure back to its equilibrium position. We describe our investigation of the RAO of a pre-designed duct, and conducted a preliminary design of a SPM system for duct-type TCP in shallow water. Many studies have been performed of mooring system designs based on numerical simulation and experimental methods. Cunff et al. introduced a frequency domain analysis methodology for moored floater motion [6]. Yang conducted hydraulic model experiments in order to analyze the hydrodynamics of mooring lines [7]. Recently, mooring designs of floating offshore wind turbines have been investigated [8], [9].

Because of the advantages of simple installation, ease of retrieval, and a robust weather vane mechanism, an SPM system can operate in various areas. For shallow water of less than 30 meters, SPM also has advantages of cost effectiveness compared with fixed structure supporting types. Thus, we propose a floating and mooring method to fix a floating duct-type TCP system. A floating duct-type TCP was modeled in panel mode, and a global response analysis was performed for a system consisting of a hydro-model and a mass model. After global hydrodynamic analysis, the mooring system concept was investigated. System behavior was analyzed using the Wadam and OrcaFlex commercial software programs.

II. Duct for TCP System

A. Duct Design Specification

The proposed streamline-shaped duct induces wakes at the end of the duct and amplifies the current velocity. A 120% amplification of the stream velocity was observed based on CFD simulation. This duct was developed by combining a nozzle and diffuser that has an open inlet and outlet, respectively. The minimum inner diameter of the duct was determined by considering a turbine size of 1.96 m and a maximum duct outer diameter of 4 m. Fig. 1 shows the analysis result for the duct. Table I gives the specifications of the duct.

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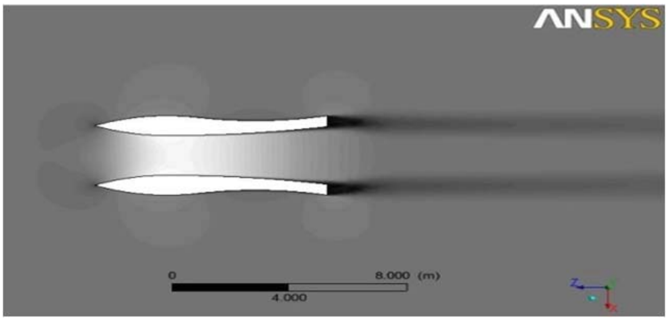

Fig. 1 CFD analysis for streamline-shaped duct

TABLE I
DIMENSIONS OF DUCT STRUCTURE

Symbol	Description	Specification
D_I	Inner diameter	2 m
D_O	Outer diameter	4m
L	Length	4.876 m
M	Mass with ballast water	52.4 ton
B	Buoyancy	55.5 ton

B. Motion of the Duct

In a preliminary design of a mooring system, the characteristic motion of the floater should be investigated. Fig. 2 shows a simplified procedure for mooring system design.

Fig. 2 Simplified procedure for mooring system design

If the motion of the floater is unstable fin stabilizer or ballasting method can be used for stabilization. The elements of a mooring system should be designed in detail, including the design of the fairlead point and touch down point, and the selection of material.

The RAO for six degree-of-freedom motion of a duct was analyzed by using Wadam software. Table II shows the environmental conditions for the RAO analysis.

TABLE II
ENVIRONMENTAL CONDITIONS FOR RAO ANALYSIS

Description	Specifications
water depth	30 m
position	-10 m
wave direction range	0 to 180°
wave period range	2 to 30 s
wave length range	6.24 to 503 m
kinematic viscosity of water	1.19e-6 m^2/s

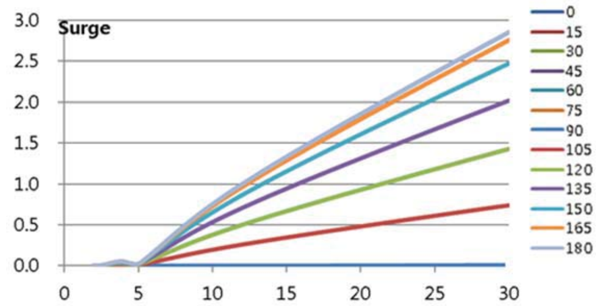

Fig. 3 Surge RAO of proposed duct

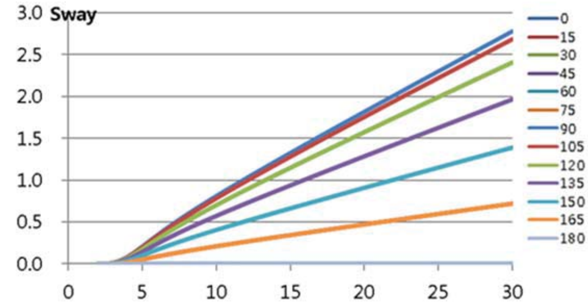

Fig. 4 Sway RAO of proposed duct

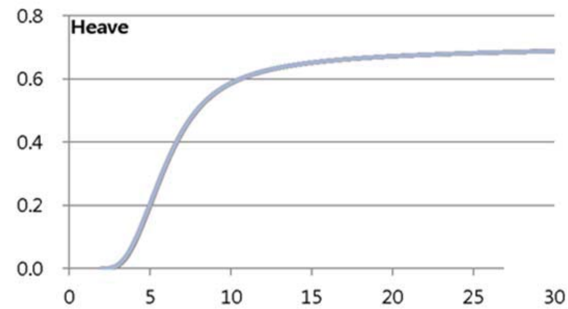

Fig. 5 Heave RAO of proposed duct

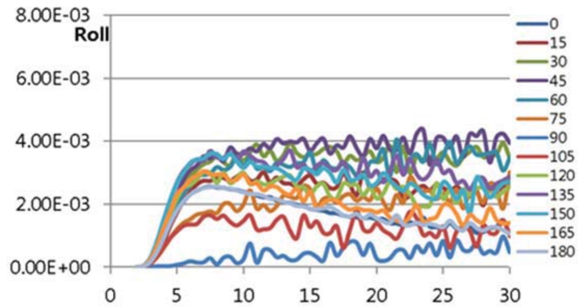

Fig. 6 Roll RAO of proposed duct

As Figs. 3-8 show, the surge and sway motion of the duct is dominant with respect to the wave period and direction. Also, the RAO amplitude is proportional to the wave period. Similarly, heave motion is proportional to the wave period, but roll for the proposed duct is irregular because of its symmetric mass distribution about the x-axis. For pitch motion, the duct has a peak at a wave period of about 6s. The yaw motion is independent with respect to the wave period and direction.

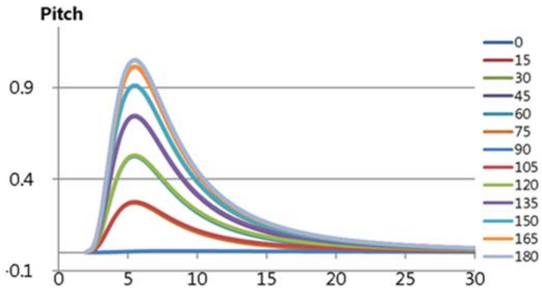

Fig. 7 Pitch RAO of proposed duct

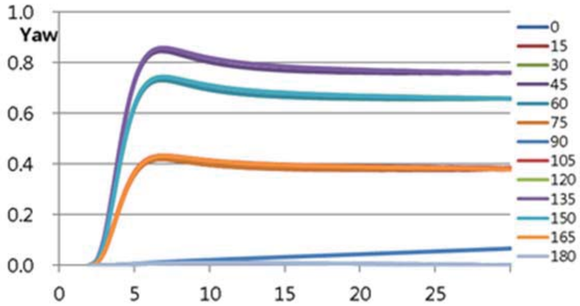

Fig. 8 Yaw RAO of proposed duct

III. Mooring Line Design

A. Mooring Ling Design

Table III shows the environmental conditions used in the mooring analysis. Currents, waves, and 30 m of shallow water were specified for the designed mooring system. The power law and TMA wave spectrum were adopted for currents and waves, respectively. Fig. 9 shows the vertical current velocity profile. The current speed at the seabed is 0.6 m/s and increased to 1.5 m/s at sea level.

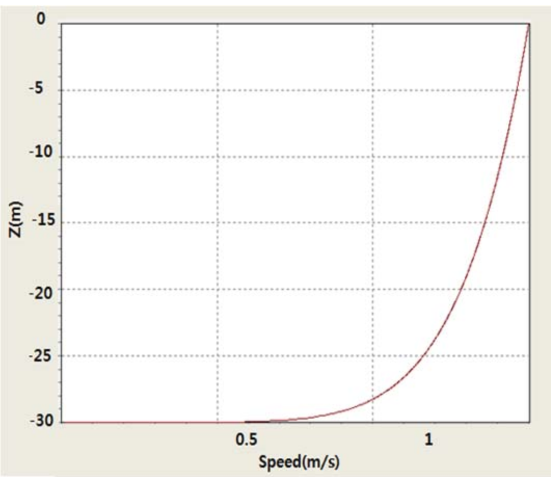

Fig. 9 Vertical current velocity profile.

The adopted TMA wave spectrum is defined by (1). The finite water depth spectrum for non-breaking waves is given by the Joint North Sea Wave Project (JONSWAP) spectrum multiplied by a depth function. For this mooring analysis, the significant wave height and wave period were assumed to be 0.7 m and 5s, respectively.

$$S_{TMA}(\omega) = \alpha g^2 \omega^{-5} \exp[-\frac{5}{4}(\frac{\omega_p}{\omega})^4 + (\ln(\gamma)) \exp\left(-\frac{1}{2}\left(\frac{\omega-\omega_p}{\sigma(\omega)\omega_p}\right)^2\right)\Big] \quad (1)$$

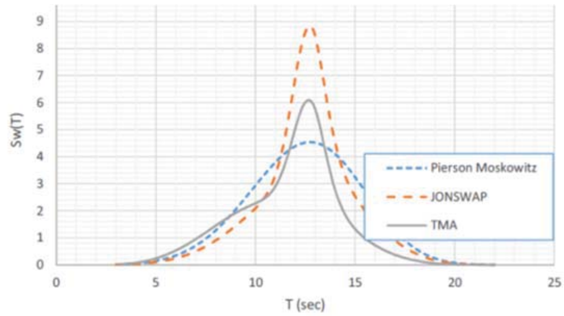

Fig. 10 Comparison of wave spectra

TABLE III
ENVIRONMENTAL CONDITIONS FOR MOORING ANALYSIS

Description	Specification
Seabed stiffness	100 kN/m/m^2
Current speed at sea level	1.5 m/s
Current speed at seabed	0.6 m/s
Significant wave height	0.7 m
Significant wave period	5 s

B. Fairlead Point Optimization

The fairlead point is one of the most important design parameters because the high tension applied at the fairlead point and the motions of a single point moored floater are affected by the fairlead point.

With a 1m interval of the fairlead point, five cases were set and analyzed. As Fig. 11 shows, fairlead points were located from 0 to 4 meters apart from the inlet of the duct.

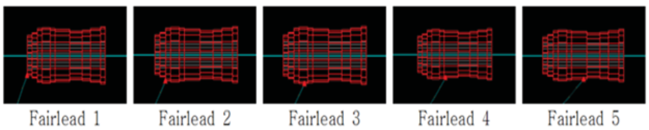

Fig. 11 Fairlead point for five cases

Table IV shows the maximum surge, heave, and pitch motion.

TABLE IV
MOTION OF FLOATER WITH FAIRLEAD POINT

	Fairlead point				
	0 m	1 m	2 m	3 m	4 m
Surge	1.25	1.38	1.50	1.24	10.88
Heave	2.10	2.23	2.23	2.18	2.67
Pitch	12.45	10.35	8.10	10.92	179.83

In case 3, the fairlead point was located 2m from the inlet of the duct with an 8.12° minimum pitch motion. Therefore, the third case, having the smallest pitch motion, was adopted for the SPM system.

C. Mooring Line Length Optimization

The designed mooring line consists of 100 mm of studless R3S chain and 100 mm of Dyform DB2K steel wire. Table V shows the specification of the chain and steel wire.

TABLE V
SPECIFICATION OF MOORING LINE

	Nominal Diameter (mm)	Outer diameter (mm)	Unit mass (te/m)	Allowable tension (kN)	Axial stiffness (kN)
Studless R3S Chain	0.1	0.18	0.04	2.988	854000
DYFORM DB2K Wire	0.1	0.08	0.199	2.81	404000

25m of studless chain was anchored on the seabed, and steel wire linked the chain to the duct fairlead. The steel wire length parameter was changed in order to optimize the pre-tension. Comparative analysis was conducted for wire lengths from 21 to 31m at 2m intervals. Table VI shows the maximum motion. As these results show, the case with 29m of steel wire exhibits the most stable translational and rotational motion. So, 54m of mooring line comprised of 25m of studless chain and 29m of steel wire was adopted as the optimum mooring line.

TABLE VI
MOTION OF FLOATER WITH MOORING LINE LENGTH

	Wire length					
	21 m	23 m	25 m	27 m	29 m	31 m
Surge	1.25	1.45	1.50	1.29	1.18	1.24
Heave	2.24	2.41	2.23	2.26	1.9	2.04
Pitch	8.89	9.55	8.10	9.13	8.16	8.33

D. Mooring Clamp Weight Optimization

To make floater motions stable, a clamp weight is used in a mooring system. In this study, 200 kgf of clamp weight was specified for the stabilization of the mooring system. The clamp weight volume is 0.0255 m^3, and it has 174 kgf of underwater weight. The clamp was attached from the wire and chain connection point at 2 m intervals, and 10 cases were set. Fig. 12 shows clamp weights attached to the SPM system for OrcaFlex analysis.

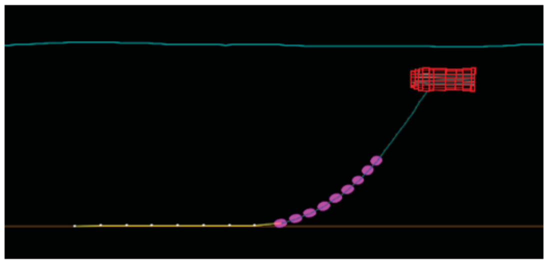

Fig. 12 Clamp weight attached to SPM system for OrcaFlex analysis

Table VII shows the maximum motion and Fig. 13 shows the tendency of the motion range versus clamp weight.

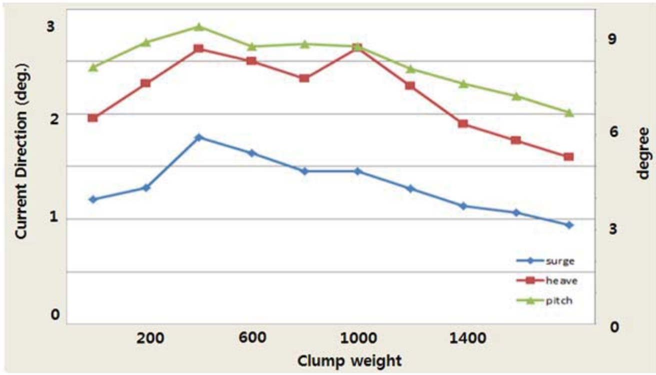

Fig. 13 Duct excursion range with clamp weight

TABLE VII
MOTION OF FLOATER WITH CLAMP WEIGHT

	Wire length									
	0	1	2	3	4	5	6	7	8	9
Surge	**1.19**	**1.30**	**1.78**	**1.63**	**1.46**	**1.45**	**1.29**	**1.13**	**1.06**	**0.95**
Heave	**1.96**	**2.29**	**2.62**	**2.50**	**2.34**	**2.63**	**2.27**	**1.91**	**1.75**	**1.59**
Pitch	**8.17**	**8.96**	**9.45**	**8.82**	**8.91**	**8.82**	**8.11**	**7.65**	**7.24**	**6.72**

The duct excursion rises sharply from 2 of clamp weights and steadily drops back to 9 of clamp weights. In the cases of clamp weight 0 to 7, the duct structure floats at the sea surface. The duct attached 9 of clamp weights sank deep compared with case 0 to 8. When the current velocity profile is considered, the vertical level of the duct is an important parameter with respect to the improvement of generating power. So 8 of clamp weight making floater keep most suitable underwater depth of 2.66 meters and TCP generate more power was adopted for the optimum SPM system.

IV. FUNCTIONAL QUALIFICATION OF MOORING SYSTEM

A. Mooring for Various Velocities

To ensure the stability of the mooring system, various current speeds were applied and the motions of the floating duct were observed. The applied current speeds have a range from 1.5 to 2.0 m/s at 0.1 m/s intervals. Because a faster current speed induces a much higher drag force, greater initial displacement was observed at a higher current speed. There is no significant fluctuation because the strong current plays a station-keeping role. Table VIII shows the maximum motion. Fig. 14 shows the tendency of each motion's range.

TABLE VIII
MOTION OF FLOATER VERSUS CURRENT SPEED

	Current speed (m/s)					
	1.5	1.6	1.7	1.8	1.9	2.0
Surge	0.94	0.83	0.74	0.66	0.60	0.54
Heave	1.58	1.41	1.29	1.17	1.06	0.96
Pitch	6.72	5.90	5.16	5.08	5.10	5.08

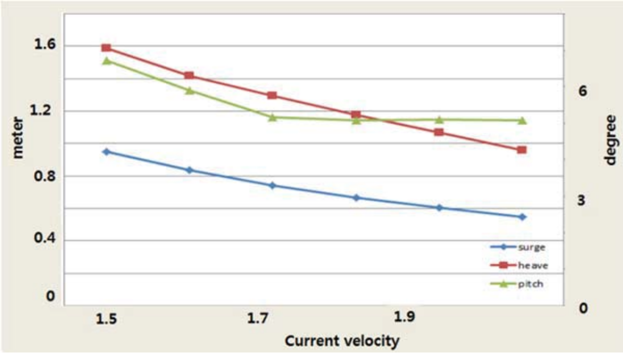

Fig. 14 Duct excursion range versus current speed

For a low current speed, the effect of the waves is relatively high. Therefore, the translational and rotational motion of the floating duct fluctuates with a time.

B. Mooring Line Structural Safety

The tension of the mooring line was investigated to check the safety of the mooring system. Fig. 15 shows the tension of the mooring line analyzed with OrcaFlex software.

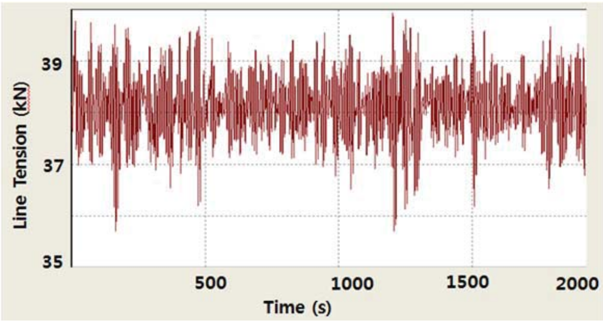

Fig. 15 Tension of mooring line

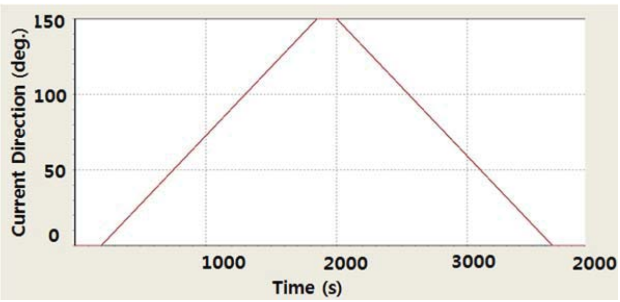

Fig. 16 Current direction change

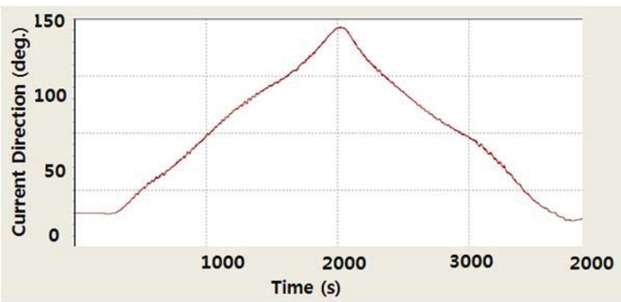

Fig. 17 Duct azimuth results

The maximum tension was 39.94 kN at the section between the fairlead point and the 100 mm steel wire. The maximum tension and displacement at the anchor point are 7.17 kN and 0 m, respectively. So, this is a safe value for a 2810 kN minimum breaking load.

C. Yawing System

Weather vanning is one of the advantages of applying an SMP system. Keeping the position passively can reduce tension and prevent buckling of the mooring line. A yawing motion test was conducted with a changing current direction. The current direction changed from 0 to 150° with an angular velocity of 0.1 rad/s, and it came back to 0° with the same angular velocity. Figs. 16 and 17 show the current direction change and the duct azimuth result, respectively, versus time.

Based on our analysis results, the designed mooring system is shown to have good weather vanning characteristics.

V. Conclusion

A SPM system was designed for 10 kW TCP devices. For a previously designed streamline-shaped duct, the dynamic motion of a single-point moored TCP duct was analyzed based on RAO analysis data for various current speeds, a TMA wave spectrum, and 30 m of shallow water condition. 2m of fairlead point, 29m of wire length, and 8 clamp weights were determined to be the optimum SPM system specifications.

A functional qualification of the designed mooring system was conducted for motion with various current velocities, and with respect to mooring line structural safety and yawing system certification. For low current velocity, the floating duct exhibits fluctuations of surge, heave, and pitch motion due to the wave effect. For high current velocity, the motions of the floater are stable with a large initial excursion. The designed mooring system shows satisfactory results with regard to mooring line structural safety and the yawing test.

The designed SPM system was confirmed to function effectively and stabilize the motions of the floater. The proposed floating duct-type TCP system can effectively generate power by reducing the installation cost. We suggest that the proposed design could be used in a variety of areas to generate power.

Acknowledgment

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