Optimal design of a submerged tidal device for low current environment

Chul-hee Jo, Seung-won Jeong, Su-jin Hwang, and Sung-ho Cho

Abstract— The tidal current power is one of the reliable renewable ocean energy resources that can be deployed at the region having ocean current. The feasible current speed for the application of tidal device is known to be more than 2m/s. As there are many islands in Asia where the current speed is below than the feasible speed, the submerged device that can produce the power at lower current speed with easy deployment and retrieve is introduce. To simplify the installation and operation and maintenance, the 4-point taut mooring system is applied that can also secure the designated position. In this study, a horizontal axis turbine of 5 kW submerged tidal device is designed and analyzed for a low current region that consist of two buoyancy tanks, a yaw control strut, and a diffuser-type brimmed duct. To analyze the most stable condition, 9 different cases of width and height of the device and 8 different mooring arrangements therefore, total 72 different cases are investigated both by frequency and time domains. The result shows that pitch angle varies from 8 to 15 degrees and the variation of yaw angle is merely existed. 9.7 percent of power reduction is expected. Pitch angle and the yaw angle is the main factor that affects the power reduction, however, as the effect of yaw angle is merely exists, optimal device is designed with only considering the pitch angle. The optimal design has 4.42 meters width, 2 meters height, 30° of azimuth angle and 60° of hang-off angle.

Keywords—**Mooring system, Optimal design, Submerged tidal device, Tidal energy, Tidal current power.**

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I. Introduction

TIDAL current power is a renewable energy resource that offers a reliable and continuous source of electricity. Unlike other renewable energy sources, tidal current power can generate electricity continuously due to the predictable nature of tidal currents, regardless of weather conditions or seasons. However, commercialized tidal energy typically requires a minimum current speed of 2 m/s.

Several studies have been conducted to expand the applicability of tidal current power to low current areas. A high-TSR (tip speed ratio) tidal turbine is developed for less energetic tidal currents with velocities less than 1.5 m/s [1]. Floating tidal turbines are developed for Kuroshio currents with a flow speed of 1 to 1.5 m/s [2]-[3]. A small-scale tidal device is also developed with a high torque turbine, a nozzle-diffuser duct, and a magnetic coupling for low current regions and demonstrated its application, which significantly lowered the cut-in speed and produced much higher power output than the ordinary HAT tidal current device. Furthermore, small-scale prototype HAT device was designed and implemented in Hong Kong, which produced electricity at a current speed of 0.4 m/s [4].

Various ducts and diffusers have applied to the device to increase incoming current velocity in lower current speed conditions. While the inlet effect of the duct is small, the influence of the diffuser is large [5]. The performance of flow velocity amplification for various duct configurations has been fully discussed [6], and the effect of curvature, thickness, and camber of the duct for the bi-directional tidal turbine on flow has been verified [7].

In addition to improve blade performance, another major research area focuses on enhancing the power output of the tidal current device. The increase of lift coefficient contributes to higher power output, while the decrease of drag coefficient and pitching moment will also help with higher power production [8]. Several studies have been conducted to verify the key factors affecting the efficiency of the tidal current power device, such as the type of the stanchion on tidal turbine [9] and the effect of wave load on device performance [10].

This paper introduces a submerged HAT tidal current device for 5 kW that aims to minimize pitch response, which mainly affects power generation. The device consists of two buoyancy tanks, a yaw control strut, a brimmed duct of diffuser type, and a four-point taut mooring system. The dynamic responses of the device with various widths and heights and mooring lines are analyzed to examine the behavior of the device, mooring line tension, and power generation.

In Korea, there are over 3,600 islands, of which only 13.2% are inhabited and only 65 islands are grid-connected by subsea power cables. The rest of the islands are dependent on diesel generators for electricity, leading to a high deficit in the government budget. To increase the self-power sufficient rate of the individual island, eco island or green island projects have been launched, encouraging renewable adaptation in the islands without electricity from the mainland. Many islands in Korea have strong current speeds of more than 2 m/s, including Uldolmok, Geocha channel, Jangjuk channel, Maenggol channel, and Heonggan channel. However, many other islands have lower than 2 m/s current speeds [11].

The device proposed in this research has the potential to be utilized in low current speed regions, not only in Korea but also in many other islands where small-scale devices could be implemented to generate electricity.

II. DEVICE MODELING

In this study, a numerical analysis was conducted on a HAT submerged tidal device to develop a 5 kW prototype for sea trials (Fig. 1) after considering various tidal device configurations from previous research. To address concerns regarding aesthetic pollution, a submerged concept below the surface was considered, and a mooring positioning arrangement was implemented to minimize installation and maintenance costs in remote island sites. Two rigidly connected pontoons were placed above the turbine to control buoyancy and tension to the mooring lines. The pontoon had bulkheads inside to regulate seawater inflow and to ensure the stabilization of the device. Additionally, a brimmed diffuser-type duct was attached to increase the incoming current speed to the turbine. Based on previous experiments, it was found that a gross buoyancy to tank weight ratio of 1.5 had applied because of its low mooring pre-tension.

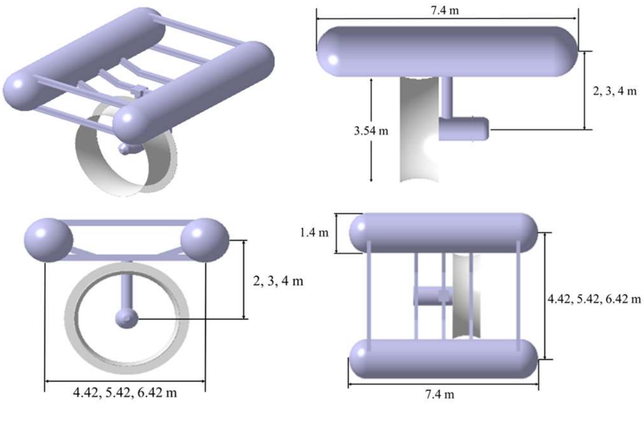

Fig. 1. Configuration of the submerged tidal device

TABLE I
SUBMERGED TIDAL DEVICE CONFIGURATION

Description	Unit	Value
Length	m	7.4
Width	m	4.42, 5.42, 6.42
Height	m	2, 3, 4
Number of buoyancy tank	ea	2
Buoyancy tank diameter	m	1.4
Turbine diameter	m	2.87
Duct outer diameter	m	3.54
Gross buoyancy to weight ratio	-	1.5

To prevent vortex creation by the mooring line and strut in front of the turbine, a minimum width of 1.0 D and minimum height of 0.5 D (where D is the turbine diameter) were established, as per [12].

Table I outlines the configuration of the submerged tidal device, with the pontoon length and diameter measuring 7.4m and 1.4m, respectively. The width is defined as the distance between the centers of two pontoons, while the height is the distance between the center of the pontoon and the turbine shaft.

The four-point taut mooring system configuration is shown in Fig. 2, with the hang-off angle and azimuth angle investigated in 8 cases (45°, 50°, 55°, and 60° for hang-off angle, and 30° and 45° for azimuth angle). Finally, Table II details the mooring configuration for the analysis in time domain responses using *OrcaFlex 11.0*.

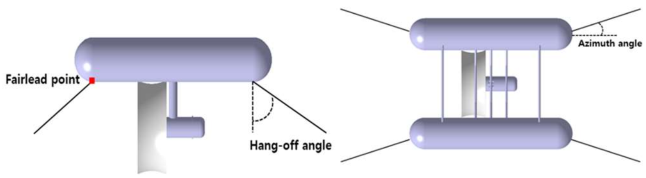

Fig. 2. Hang-off angle and azimuth angle

TABLE II
MOORING LINE CONFIGURATION

Description	Unit	Value
Azimuth angle	degree(°)	30, 45
Hang-off angle	degree(°)	45, 50, 55, 60
Length	m	16.97 to 28.00
Type	-	6X19 IWRC wire rope
Diameter	mm	30
Mass in air	kg/m	3.6
Breaking load	kN	570
Axial stiffness	kN	36,360

III. ANALYSIS CONDITION

A. Frequency domain analysis

The Response Amplitude Operator (RAO) is a key parameter in determining the dynamic response of a submerged tidal device [13]. To solve the time-domain behavior, hydrodynamic coefficients must be considered. These coefficients can be calculated using *Ansys AQWA*, which employs potential theory in the frequency domain. In this study, the analysis is carried out by considering wave periods ranging from 1 to 25 seconds with intervals of 0.5 seconds. The hydrodynamic coefficients, including RAO, added mass, and damping coefficient, are computed using frequency domain analysis. The derived coefficients are then utilized in the time-domain analysis. Table III presents the nine cases considered, with variable widths of 4.42, 5.42, and 6.42 m and heights of 2, 3, and 4 m, to optimize the dynamic behavior of the device.

TABLE III
CASE OF ANALYSIS

Case	Width	Height
4.42W2H	4.42 m	2 m
4.42W3H	4.42 m	3 m
4.42W4H	4.42 m	4 m
5.42W2H	5.42 m	2 m
5.42W3H	5.42 m	3 m
5.42W4H	5.42 m	4 m
6.42W2H	6.42 m	2 m
6.42W3H	6.42 m	3 m
6.42W4H	6.42 m	4 m

B. Time domain analysis

The study examines the effects of varying width and height values of the submerged tidal device and its mooring system on turbine thrust, drag force, and pitch moment to maximize power output. The time-domain analysis in *OrcaFlex 11.0*, is conducted using the hydrodynamic coefficients obtained from frequency domain analysis by *Ansys AQWA*. The aim is to investigate the dynamic responses of the device with different mooring configurations and maximize its power production. Table IV specifies the environmental conditions in Changseondo-Neukdo, Korea, where the study is referenced. The TMA spectrum which aligns well with observational data around Korea, is used to generate random incident waves. The thrust coefficient and turbine torque from [14] are also applied.

IV. DISCUSSION

A. Numerical analysis

Calculating the power generated by a tidal device requires considering the incoming current speed, projected area, and turbine power coefficient, as shown in (1) [15].

TABLE IV
ANALYSIS CONDITION

Description	Unit	Value
Water depth	m	20
Wave spectrum	-	TMA
Significant wave height	m	1.1
Peak period	s	3.6
Current speed	m/s	1.5
Gross buoyancy to weight ratio	-	1.5
Analysis time	s	10,800
Turbine moment	kN·m	1.176
Turbine thrust coefficient	-	0.96

$$P = \frac{1}{2}\rho A U^3 C_p \tag{1}$$

where C_p is power coefficient.

However, when the turbine is inclined against the incoming flow direction, the axial velocity component decreases, causing a reduction in power generation. Thus, the inclined angle must be taken into account when estimating power, which can be calculated using (2) [15].

$$P = \frac{1}{2}\rho A (U\cos\theta)^3 C_p \tag{2}$$

where θ is inclined angle.

The power reduction rate is proportional to the cube of the cosine of the inclined angle, indicating that the power reduction rate is highly dependent on the inclined angle. For instance, at an inclined angle of 5°, the power reduction rate is approximately 1.1%, whereas at 10°, it reaches 4.5%, and at 20°, it is 17%. These results clearly demonstrate that the inclined angle significantly affects the power output.

In assessing the performance of a submerged tidal device, the pitch and yaw angles are the major dynamic motions that affect performance [16]. As these two motions directly affect turbine performance by causing system inclination, optimizing the device configuration to minimize pitch and yaw motions is crucial.

Figures 3 to 6 illustrate the maximum pitch and yaw angles at the azimuth angle of 30° and 45°, respectively. The analysis revealed that the pitch motion has a greater impact on power reduction than the yaw motion. The maximum pitch angle of 14.8° resulted in a 9.7 % power reduction according to (2). Thus, in this study, the pitch motion is considered the main factor that affects the optimal design.

However, the results of the time-domain analysis indicated that the maximum pitch angle increased with an increase in azimuth angle of 30° and 45° for different analysis cases. The increase in the maximum pitch angle decreases as the hang-off angle, strut width, or height increases. A 5° increase in hang-off angle decreases of about 1.3° in the maximum pitch angle. Additionally, the maximum pitch angle tends to decrease with smaller widths and lower strut heights.

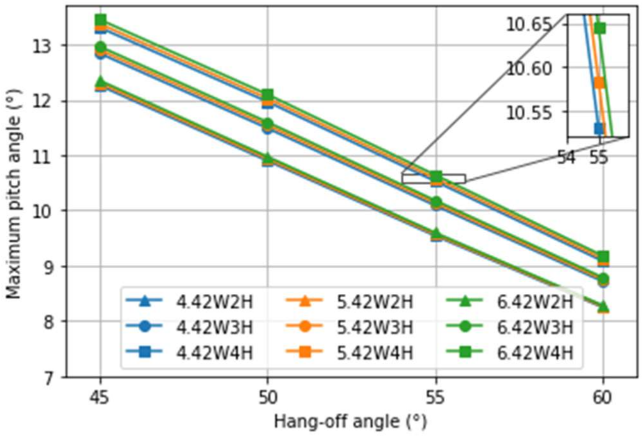

Fig. 3. Maximum pitch angle of azimuth angle of 30°

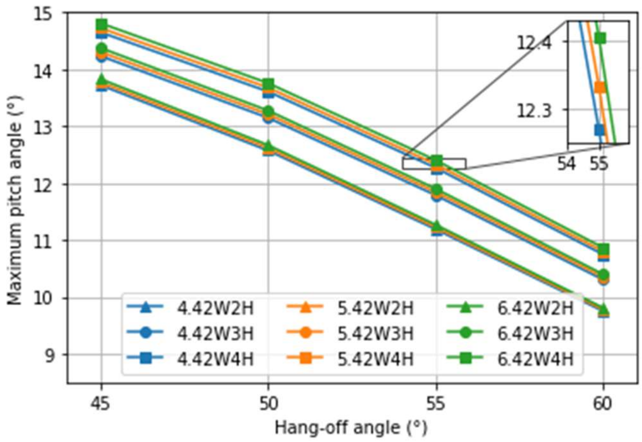

Fig. 4. Maximum pitch angle of azimuth angle of 45°

An increase in the strut height by 1 m results in an increase of approximately 0.5° in the maximum pitch angle. On the other hand, the change in width has little effect on the pitch motion, with an increase of 1 m resulting in an increase of approximately 0.04° in the maximum pitch angle.

Overall, the results suggest that the strut height is a key factor in the pitch motion, as it increases the moment arm of the turbine load.

In summary, the key factors that contribute to the dynamics of a tidal current device are the strut height, azimuth angle, and hang-off angle. Smaller strut height and azimuth angle, and larger hang-off angle lead to a reduction in pitch angle, which affects power generation. Based on the given configuration, the optimal design for the submerged tidal device is determined as an azimuth angle of 30°, hang-off angle of 60°, width of 4.42 m, and

TABLE V

RESULTS OF 6-DOF TIME DOMAIN ANALYSIS OF OPTIMAL DESIGN

Case	Maximum	Average
Surge	0.4904 m	0.2050 m
Sway	0.0002 m	0.0000 m
Heave	0.2270 m	0.2270 m
Roll	0.0017°	0.0000°
Pitch	8.3653°	4.6529°
Yaw	0.0004°	0.0000°

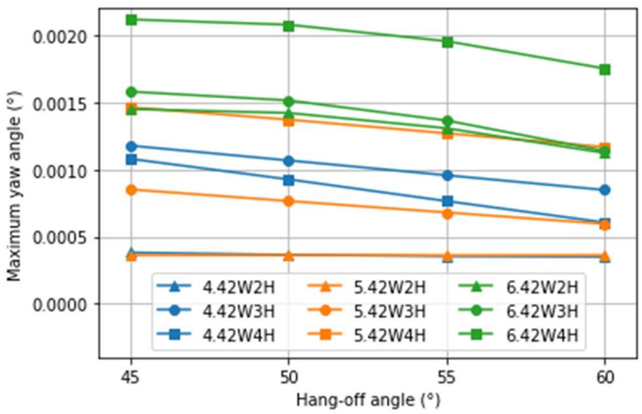

Fig. 5. Maximum yaw angle of azimuth angle of 30°

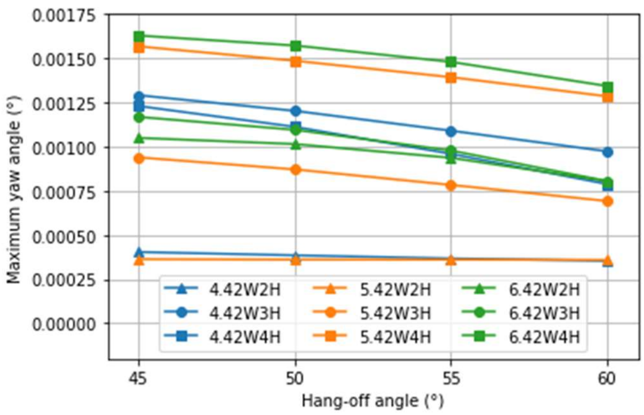

Fig. 6. Maximum yaw angle of azimuth angle of 45°

height of 2 m. Table V shows a summary of the dynamic motions resulting from the time-domain analysis of the optimal design.

The impact of pitch motion on power generation is analyzed along with the estimated power generation. Figure 7 displays the time series of pitch angle and power generation in the optimal design. The average pitch angle is approximately 4.65°, and the estimated average power is 4.764 kW with a power reduction rate of 4.716 % in the optimal design. Table VI and VII present the average power reduction rate for each analysis case, and the optimal design shows the least power reduction.

B. *Sea trial*

The prototype of the proposed device was built and tested in the sea condition to validate the dynamic behavior and power generation of the optimized device in Changseondo-Neukdo area in Korea. Figure 8-10 show the manufacturing, device transport, anchoring and device installation procedure for the sea trial tests.

The performance of the device is presented on the monitoring panel and the measure data is recorded in the hard disk as shown Fig. 11. The monitoring panel shows power output, efficiency for turbine, system, and duct. The duct efficiency represents the amplified velocity ratio from the incoming velocity. In Fig. 11, the duct efficiency is 119.7 % meaning the flow velocity after the duct is increased 119.7 % from the incoming velocity. The power

TABLE VI
POWER REDUCTION RATE OF AZIMUTH ANGLE OF 30°

Case	Hang-off angle 45°	Hang-off angle 50°	Hang-off angle 55°	Hang-off angle 60°
4.42W2H	7.041 %	6.107 %	5.317 %	4.716 %
4.42W3H	8.008 %	6.945 %	5.991 %	5.218 %
4.42W4H	9.002 %	7.824 %	6.715 %	5.774 %
5.42W2H	7.094 %	6.147 %	5.345 %	4.734 %
5.42W3H	8.077 %	6.999 %	6.031 %	5.246 %
5.42W4H	9.080 %	7.887 %	6.764 %	5.809 %
6.42W2H	7.149 %	6.188 %	5.374 %	4.754 %
6.42W3H	8.146 %	7.054 %	6.072 %	5.274 %
6.42W4H	9.164 %	7.955 %	6.817 %	5.847 %

TABLE VII
POWER REDUCTION RATE OF AZIMUTH ANGLE OF 45°

Case	Hang-off angle 45°	Hang-off angle 50°	Hang-off angle 55°	Hang-off angle 60°
4.42W2H	8.228 %	7.277 %	6.297 %	5.428 %
4.42W3H	9.273 %	8.270 %	7.167 %	6.126 %
4.42W4H	10.330 %	9.287 %	8.075 %	6.874 %
5.42W2H	8.297 %	7.333 %	6.340 %	5.458 %
5.42W3H	9.359 %	8.343 %	7.224 %	6.169 %
5.42W4H	10.424 %	9.369 %	8.141 %	6.925 %
6.42W2H	8.368 %	7.392 %	6.385 %	5.489 %
6.42W3H	9.445 %	8.415 %	7.282 %	6.212 %
6.42W4H	10.525 %	9.456 %	8.213 %	6.980 %

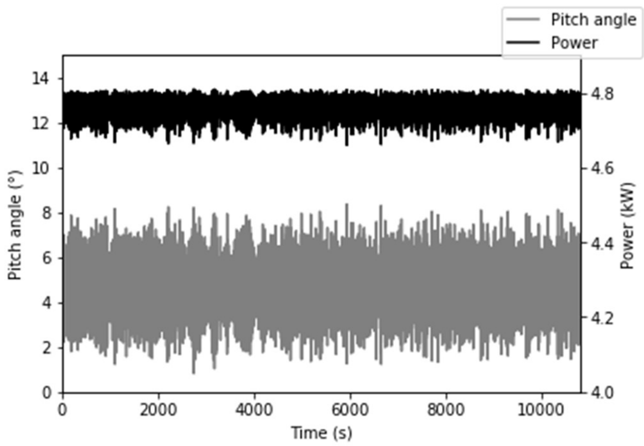

Fig. 7. Time series of power and pitch angle in optimal design

generated of 5.7 kW is shown at the particular moment in Fig. 11. The test results satisfy the designed power output generating more than 5 kW. After getting initial data measurement, the electrical system was failed during sea trial causing to end the test.

V. CONCLUSION

In this paper, an optimization study is presented for a 5 kW submerged tidal device supported by a four-point taut mooring system that includes a duct and mooring arrangement for improved power generation. The device consists of two pontoons, a yaw control system, and a brimmed diffuser duct. Hydrodynamic coefficients of the device were calculated for various heights and widths using frequency domain analysis, and dynamic responses of the device were simulated with different mooring line configurations to optimize the device and mooring system for maximum power production rate.

Fig. 8. Manufacturing procedure for sea trial

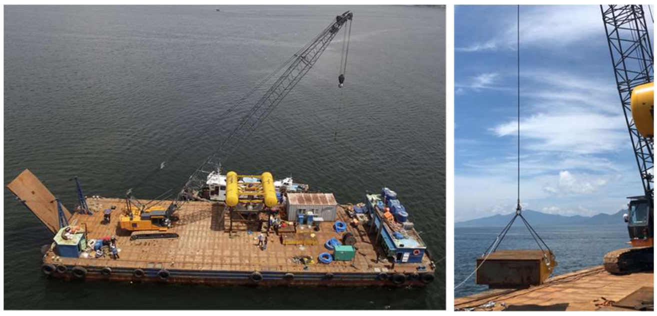

Fig. 9. Device transport (left) and anchoring procedure (right)

Fig. 10. Installation procedure for sea trial

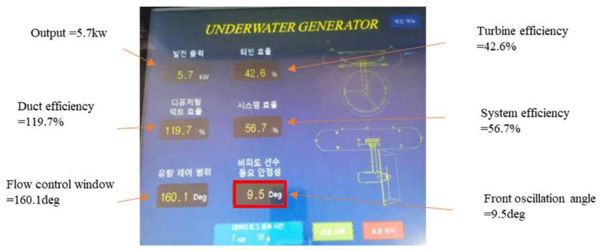

Fig. 11. Data monitoring panel

The study found that the strut height, azimuth angle, and hang-off angle are the primary factors influencing the dynamic behavior of the tidal current device. As the strut height and azimuth angle decrease, and the hang-off angle increases, the pitch angle that affects power generation is reduced, resulting in a reduction in power loss. The optimal design was determined to have an azimuth angle of 30°, a hang-off angle of 60°, and a height of 2 m, resulting in the smallest pitch angle of 8.36°. The width of the device had little effect on the dynamic response due to the taut mooring system. The average power of the optimal device was 4.764 kW with a power reduction rate of 4.71 %.

The proposed device was tested in the Chanseondo-Neukdo area in Korea and validated the duct efficiency of 119.7 % with a power output of 5.7 kW that exceeds the designed output of 5 kW. Unfortunately, the electrical system failed during the sea trials, but the initial results show the potential of the device for applications.

Overall, this study provides insights into the key factors influencing the performance of submerged tidal devices and offers an optimized design for improved power production.

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