A numerical study on performance improvement of counter-rotating type tidal stream power unit

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Abstract. One of the forms of ocean energy, tidal stream energy is attracting attention as a sustainable, predictable and eco-friendly ocean energy source. Unique tandem propellers that can counter-rotate have been designed to generate electric power effectively from a tidal stream. This type of power unit has several advantages compared to the conventional unit with a single propeller and the increase in efficiency of counter-rotating type tidal stream power unit has already been proven. The counter-rotating type tidal stream power unit has a complex interrelationship between the front and rear propeller contrary to the conventional single propeller type tidal turbine. Such as, the no-load area on the front propeller, the diameter ratio of front and rear propeller and the rotational speed of each propeller, etc.. And the inlet condition of the rear propeller is very important to improve the efficiency. Thus, we have to consider these parameters to optimize tidal stream power unit. In this research, the numerical optimization algorithm with response surface method and adaptive single-objective optimization method are applied to obtain desirable propeller performance.

1. Introduction

Global warming is a big problem around the world. Due to an increasing demand in clean energy and rising fuel prices, more research is focused on renewable energy resources. Tidal stream energy is one type of renewable energy.

Among many renewable energy sources, tidal stream energy is continuous, predictable and eco-friendly ocean energy. Its energy density is higher than other renewable energy resources, and it is easy to convert into other types of energy. [1] Tidal stream is caused by the flood and ebb of a tide due to the gravitational pull of the moon. The tidal stream power unit is placed in the path of tidal stream to generate electricity, the power unit generates electricity by converting the horizontal tidal current flow into the rotational motion using propeller and generator.

Since the past one decade, many research efforts have been carried out to develop high-efficiency tidal current turbine. Now, various pilot test turbines have been developed and a number of projects are underway for commercialization in the coastal areas of UK and Europe, which have abundant tidal current energy resources.

A unique counter-rotating type tidal stream power unit was proposed by Kanemoto et al. [2-5] This tidal stream power unit has the tandem propellers and the peculiar synchronous generator with double rotational armatures.

Numerical optimization method coupled with the response surface method and the genetic algorithm has been recommended to provide for the optimization of the original blades designed by
BEM theory, it has been proven to be successful in the design of wind turbines [6,7]. Huang used the response surface method and multi-objective method to improve the efficiency of the tidal turbine [8,9]. In this research, it is adopted the blade yaw angles and the distance of the front and rear propellers simultaneously and compared the turbine efficiency with the optimized model and the baseline model.

![Figures showing blade profiles of the counter-rotating type propellers](image)

**Figure 1.** Blade sectional profiles of the counter-rotating type propellers

2. **Numerical Analysis**

Figure 1 shows the blade profiles of the front and the rear propellers and the sectional shapes between the blade hub to the blade tip. The front propeller is made up of 3 blades and the rear propeller consists of 5 blades. The diameter of front propeller is 500 (mm), and the rear one is 450 (mm). The size of the rear propeller is smaller than the front propeller. The counter-rotating type propellers have a torque balance between the front and rear propellers. So to increase the torque of the rear propellers, it is created by increasing the number of blades to 5.

Figure 2 shows the numerical domain of counter-rotating propeller model. The Flow passage angle includes the front blade and rear blade is different. Because of the number of blade has 3 at front blade and 5 at rear blade. The angle of flow passage, front blade region has 120 degree and 72 degree of rear blade region. The numerical domain size is set the 3R to upstream, 7R to downstream and 5R to radial direction. Periodic boundary condition is adopted to reduce of the usage of computing resources.

Figure 3 shows the grid system of the counter-rotating type propellers model for analysis. The hybrid grid system is used for the grid structure. Hexahedral mesh has been used for the outer region and tetrahedral mesh and prism layer is constructed in the near blade region. The number of grids is about 4,229,000 cells. For all cases, we set the y+ value under 10.

The boundary condition of the inlet is set as a velocity of 9.75 (m/s). An outlet boundary has atmospheric pressure. For the calculation of the same situation with the experimental status, we used air as a working fluid to compare to experimental results. The density of air is 1.225 (kg/m³).

The SST(Shear Stress Transport) turbulence model is adopted due to its known superior standards and its reliability to model flows having higher shear stress and to predict accurate results for flow separation under an adverse pressure gradient. To analysis the rotating effect of the flow fields, the frozen rotor method is applied for the rotating problem. The cell-centered finite volume method with a pressure-based velocity-pressure coupling algorithm was adopted. The solution gradients at the cell centers were evaluated by the cell center-based Green Gauss method. The convection term was
discretized using the second order accurate upwind scheme, and for diffusion terms, a central differencing scheme was used. The simulation was performed using ANSYS CFX V17.2, a commercial CFD software package. [10]

To estimate the efficiency, we calculated the power coefficient related tip speed ratio. The equation is as follows. Where $\lambda$ is tip speed ratio, $\omega$ is rotating speed [rad/s], $R$ is radius of blade, $C_p$ is power coefficient, $T$ is torque [Nm], $A$ is propeller swept area [$m^2$], $V_{in}$ is inlet wind velocity [m/s], $\rho$ is fluid density [kg/m$^3$], subscript $f$ is front propeller, $r$ is rear propeller.

$$\lambda_f = \frac{\omega_f R_f}{V_{in}}$$  \hspace{1cm} (1)

$$\lambda_r = \frac{\omega_r R_r}{V_{in}}$$  \hspace{1cm} (2)

$$\lambda = \lambda_f + \lambda_r$$  \hspace{1cm} (3)

$$C_{p_f} = \frac{T_f \omega_f}{(1/2) \rho V_{in}^3 A_f}$$  \hspace{1cm} (4)

$$C_{p_r} = \frac{T_r \omega_r}{(1/2) \rho V_{in}^3 A_f}$$  \hspace{1cm} (5)

$$C_p = C_{p_f} + C_{p_r}$$  \hspace{1cm} (6)

In the previous research, the author investigated the efficiency for the single and counter-rotating type tidal stream power unit using CFD method. The results showed good agreement with experimental results. We used the case of best efficiency points as a baseline design point.

3. Optimization technique and results
To improve the efficiency of the counter-rotating type tidal stream power unit, it has adopted numerical optimization technique coupled with a response surface method (RSM) and direct optimization method supported by ANSYS Design Explorer. As an objective function, we set the power coefficient and the 4 input variables (front blade yaw angle, rear blade yaw angle, front blade distance of upstream wise position and distance of rear blade downstream wise position). First for the response surface optimization, we used 25 samples for design of experiment (DOE) and latin hypercube sampling model is used. The response surface method (RSM), which is composed of a
series of statistical and mathematical method, was used as neural network algorithm to establish a relationship between input variables and objective function. Figure 4 plots the optimal results of RSM analysis.

The optimization by Nonlinear Programming by Quadratic Lagrangian (NLPQL) model was carried out to obtain the optimal blade angles and blade distance. For the second method of optimization, we used the direct optimization method. It adopted the Adaptive Single-Objective (ASO) optimization method. This method is a hybrid optimization method using optimal space-filling design, a Kriging response surface, MISQP(Mixed-Integer Sequential Quadratic Programming) and domain reduction in a direct optimization system. It has used 15 samples as an initial case. To obtain the most favourable outcome, a total of 300 cases are used. Figure 5 shows the history of the Adaptive Single-Objective method at achieving the optimal solution. We can see the progress to convergence by iterative calculation.

Table 1 shows the optimized results from the Response Surface Method and the Adaptive Single-Objective method.

|                | Front blade yaw angle | Rear blade yaw angle | Front blade distance | Rear blade distance |
|----------------|-----------------------|----------------------|----------------------|---------------------|
| Baseline model | Initial               | Initial              | 0                    | 0                   |
| RSM            | -1.3468               | -4                   | -10                  | 10                  |
| ASO            | -2.0237               | -2.1722              | -9.0669              | 7.2045              |

Table 1. Optimization results

![Figure 4](image_url)  **Figure 4.** Response surface chart for power coefficients related to front blade yaw angle and rear blade yaw angle

![Figure 5](image_url)  **Figure 5.** Adaptive Single Optimization history

We recalculated CFD simulation using this optimized input variables and compared the results with baseline model. Figure 6 represents the power coefficient distribution by RSM, ASO method and baseline model. The $C_p\text{_{ref}}$ means the maximum coefficient of $C_p$ of baseline model. The best power coefficient value from the optimized results had increased by about 5% compared to the baseline model at the best efficiency point. RSM and ASO method show good results for the entire tip speed
ratio compared to the baseline model. But the ASO method will require more computational time in comparison to the RSM optimization method.

![Power coefficient distribution by optimization](image)

**Figure 6.** Power coefficient distribution by optimization

4. **Conclusion**

In this study, numerical optimization was carried out to enhance the performance of the counter-rotating type tidal stream power unit. The geometry related to the blade yaw angles and distance of front to rear propellers were considered to optimize. The results are summarized as follows.

1. The best power coefficient value by optimized results is increased about 5% compared to the baseline model.
2. The two optimization methods display satisfactory results and optimization using Response Surface Method (RSM) is an economically beneficial way to compare the Adaptive Single-Objective (ASO) Optimization method.
3. In the future, we need a more detailed research, in which using various input variables and optimization method to obtain a more accurate optimization solution.

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