Development of a model counter-rotating type horizontal-axis tidal turbine

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Abstract. In the past decade, the tidal energies have caused worldwide concern as it can provide regular and predictable renewable energy resource for power generation. The majority of technologies for exploiting the tidal stream energy are based on the concept of the horizontal axis tidal turbine (HATT). A unique counter-rotating type HATT was proposed in the present work. The original blade profiles were designed according to the developed blade element momentum theory (BEMT). CFD simulations and experimental tests were adopted to the performance of the model counter-rotating type HATT. The experimental data provides an evidence of validation of the CFD model. Further optimization of the blade profiles was also carried out based on the CFD results.

1. Introduction
Ocean energy resources have attracted great attention to get sustainable society with accompanying hydro, wind and solar resources, and then many kinds of the power unit have been provided for the tidal stream [1]-[4].

The unique tidal stream power unit called “Counter-Rotating Type Tidal Stream Power Unit” has been proposed in the previous studies [5, 6]. As shown in Fig.1, tandem propellers counter-drive double rotational armatures respectively, in keeping the rotational torque counter-balance between both propellers/armatures. The counter-rotating type tidal stream power unit has fruitful advantages as follows: (1)The tandem propellers may be easy to suppress the cavitation rather than the single propeller, because the individual rotational speed can be reduced by about half while the armature diameter and the induced voltage are the same as those of the traditional power unit with single propeller. (2)The individual rotational speed can be designed freely in response to the tidal circumstances. (3)The rotational moment hardly acts on the casing and/or the pile because the rotational torque between both propellers/armatures is counter-balanced in the unit. That is, the unit can be mounted easily on the mono-pile. (4)The flow has scarcely the swirling component and the disturbed wave downstream of the unit, because the angular momentum change, namely the rotational torque, through the front propeller is almost the same as that through the rear propeller. That is, the flow discharges in the axial direction while the tidal stream has no swirling component.

In the present work, the front and rear propellers of counter-rotating type tidal stream power unit were designed according to BEMT. And then CFD simulations and experimental tests were adopted to the performance of the model counter-rotating type HATT.
2. Turbine design

A model counter-rotating type HATT with the diameter of 500 mm was designed as a trade-off between maximizing the Reynolds number and not incurring excessive tunnel blockage correction [7, 8]. The blade profiles were composed of the blade element KIT001 with three different relative thicknesses as shown in Fig. 2. The blade profiles of the model counter-rotating type HATT designed by BEMT are illustrated in Fig.3.

The diameter of the front propeller is $d_F = 500\text{mm}$ and the rear propeller is $d_R = 420\text{mm}$, namely the diameter ratio $[=d_R/d_F]$ is 0.84. The number of blades for upstream propeller and downstream propeller is $Z_F = 3$ and $Z_R = 5$, respectively. The axial distance between the front and the rear propellers is set to 80mm, and the diameter of the hub is set to 90 mm.
3. Performance obtained by CFD and experimental tests

In order to obtain the hydrodynamic performance of the model counter-rotating type HATT designed in the previous section, CFD simulations and experimental tests were carried out in this section. The detailed introduction of CFD simulations can refer to the published works [5, 6]. And at this stage the experimental tests were conducted in the wind tunnel in Kyushu Institute of Technology as shown in Fig.4.
Fig. 5 shows the performance of the designed model counter-rotating type HATT in terms of power coefficient. It can be seen that the trend of the power coefficient shows good agreement over a range of tip speed ratios. However, the CFD over predicts the power coefficient in the high tip speed ratio region. It should be noted that in the wind tunnel tests, there is no blockage effect and lower Reynolds number than that in the water tunnel. These differences lead to the deviation between CFD predictions and experimental results.

4. Effects of Reynolds number

Consideration was tried about the way to presume the output coefficient of the actual machine size from model test outcome. When converting from model test to actual performance, it is necessary to know the difference from the similarity law (size effect) due to the fact that the Reynolds number is different. The efficient conversion formula to predict efficient difference between a model and an actual machine has been announced from the old days. Among these the next Moody 1/5th power formula obtained empirically to a water turbine has been also used much to a pump as well as a water turbine about the total efficiency.

$$\eta = 1 - (1 - \eta^{'}) (D/D')^{1/5}$$  \hspace{1cm} (4-1)

Here $\eta$: The total efficiency and the $D$: representative size and the symbol ' indicates a model. Formula (4-1) can be transformed into following equation.

$$(1-\eta)/(1-\eta^{'}) = (Re/Re^{'})^{1/5}$$  \hspace{1cm} (4-2)

Here -1/5 of the index corresponds to a relation between friction coefficient $\lambda$ on a flat smooth board and Reynolds number $Re (\lambda \propto Re ^{-1/5})$.

Based on the above, we examined the effect of Reynolds number based on the flow analysis around the two-dimensional blade profile. For a two-dimensional blade profile, we designed the camber blade profile (Basic thickness form: NACA65-010, Mean line: NACA Mean Line 65, Chord length: 50mm, Trailing edge radius: 0.5mm) to show in figure 4-1. With analysis code, ANSYS 14.5 was used.
The analysis condition angle ($\alpha = 0 \sim 12$ deg) did the attack number ($Re = 10^4 \sim 10^5$) was $10^7$.

equivalent to the former model $Re = 10^6 \sim 10^7$ test range [9], assumed a future actual power unit (Propeller diameter is on the order of 10m).

An analysis result of lift coefficient $C_l$, drag coefficient $C_d$, and pressure coefficient $C_p = \Delta P / (0.5 \rho v^2)$ is indicated in Fig.7.

As shown in Fig.7(a), $C_l$ of $Re = 10^4$ is the small value extremely compared with other $Re$. According to the analysis result of the streamline, in the case of $Re = 10^4$, separation is seen near trailing edge in an analysis range of $\alpha$. But this separated region greatly decreases if it becomes more than $Re = 10^5$. Further, when it'll be the actual power unit size level of $Re = 10^6 \sim 10^7$, the curves are overlap each other, and influence of Reynolds number doesn't show.

As shown in Fig.7(b) and (c), $C_d$ and $C_p$ of $Re = 10^4$ is the big value extremely compared with other $Re$. $C_p$ also shows the same trend as $C_d$, the decrease amount becomes smaller as the Reynolds number increases. It has a tendency to approach saturation.

Here, we consider the relation between above-mentioned CFD result and Moody 1/5th power formula. The left-hand side of $(1 - \eta)/(1 - \eta')$ in equation (4-2) represents a loss ratio of actual and model. So this parameter is considered to be physically associated with pressure coefficient ratio $C_p / C_p'$ of actual and model. We show a rearranging result in Fig.7(d). In addition, $C_p / C_p'$ varies a little according to an attack angle, but the tendency is almost the same.

By the two dimensional blade profile which simplified that effects of the centrifugal force are not considered at all, the CFD result is similar of Moody 1/5th power formula as shown in Fig.7 (d). From this, efficiency improvement by the scale effect of the future actual power unit ($Re = 10^6 \sim 10^7$) is expected.
5. Conclusions
In the present study, a unique counter-rotating type HATT was proposed and the blade profiles were designed based on the BEMT. Both of CFD simulations and experimental tests in the wind tunnel have been carried out to verify our design. Effects of Reynolds number have also been conducted on a 2D hydrofoil, which provides a reference for the efficiency conversion from model to prototype turbine.

References
[1] Fraenkel, P.L., 2007 Marine current turbines: pioneering the development of marine kinetic energy converters, *Journal of Power and Energy*, Vol. 221, No. 2, pp. 159-169.
[2] Bahaj, A.S., Molland, A.F., Chaplin, J.R. and Batten, W.M.J., 2007 Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank, *Renewable Energy*, 32, pp. 407-426.
[3] Clarke, J., Connor, G., Grant, A., Johnstone, C., Ordonez-Sanchez, S., 2008 Contra-rotating marine current turbines: performance in field trials and power train developments, *Proceedings of 10th World Renewable Energy Congress*, (Glasgow, Scotland, UK).
[4] Hiraki, K., Wakita, R., Kanemoto, T., 2012 Demonstrative power generation by twin-runner darrieus turbine in Kanmon strait, *Proceedings of the 22nd International Offshore and Polar Engineering Conference*, (Rhodes, Greece), pp.725-729.
[5] Huang, B., Kanemoto, T., 2015 Multi-objective numerical optimization of the front blade pitch angle distribution in a counter-rotating type horizontal-axis tidal turbine, *Renewable Energy*, 81, pp.837-844.
[6] Huang, B., Kanemoto, T., 2015 Performance and internal flow of a counter-rotating type tidal stream turbine, *Journal of Thermal Science*, 24(5), pp.1-7.

[7] Bahaj, A.S., Molland, A.F., Chaplin, J.R., Batten, W.M.J., 2007 Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank, *Renewable Energy*, 32(3), pp.407-426.

[8] Bahaj, A.S., Batten, W.M.J., McCann, G., 2007 Experimental verifications of numerical predictions for the hydrodynamic performance of horizontal axis marine current turbines, *Renewable Energy*, 32(15), pp.2479-2490.

[9] Usui, Y., Kanemoto, T., Takaki, K. and Hiraki, K., 2014 Counter-rotating type tidal stream power unit mounted on a mono-pile, *Journal of Energy and Power Engineering*, pp.1748-1755.