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Performance of counter-rotating tandem propellers at oblique flow conditions

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Performance of counter-rotating tandem propellers at oblique flow conditions

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Abstract. Tidal currents are a potential source of reliable and renewable energy. Various power generation systems have been proposed. The authors developed a counter-rotating type tidal stream power unit in which the tandem runners make the inner and the outer armatures counter-rotate. The unit is composed of tandem propellers with 3 front and 5 rear blades and has a promising advantage that the rotational torque between the front runner and the rear propellers, namely the inner and the outer armatures, is balanced in the unit. That is, this tidal stream power unit can be moored with only one cable and then its nose and tail will naturally line up in response to the tidal stream by yawing. In this paper, the performance of the propellers in oblique flow conditions were investigated experimentally and numerically. When the coming flow obliquely to the propeller by 30 degrees, the performance deteriorates by 20%.

Keywords: Performance, Tidal currents, Counter-rotating, Tandem propellers, Oblique flow

1. Introduction

The necessity of alternative energy is increasing every day due to depletion of fossil fuels and global warming caused by an increase in carbon dioxide emissions. Ocean energy is a clean energy source with higher conversion efficiency and energy density compared to other renewables. These sources also have the advantage of the reliability of the natural phenomena. Many types of energy conversion have been proposed to capture the energy that can be used in the ocean. Horizontal axis turbines are the most advanced technology and their operating principles are very similar to that of wind turbines. We can take advantage of the advanced technology in the wind power industry to our benefit. These designs are the closest to commercial realization [1].

Kanemoto, et al [2, 3] provided the counter rotation type unit described above and applied it to the ocean, wind power and hydraulic power. This unique tidal power plant proposed by the author uses contra rotating armature that rotate at the same speed as conventional generators. Cavitation may occur in water, but it can be suppressed by decreasing the diameter and decreasing the propellers speeds. By using a generator of the same size as the existing generator, it is possible to obtain a higher induced voltage at a high relative rotation speed. An important advantage of this generator is that the rotational torque of the front propeller coincides with to torque of the rear propeller ~~s~~o there is no reaction force. Galloway, et al performed a performance and thrust test in a towing tank in the direction of the turbine axis [4, 5]. Tian, et al compared the difference in performance and thrust according to flow angle and turbulence intensity via CFD [6].

The tidal stream direction may change randomly over small time ranges, and ebbs and flows in directions that are not always perpendicular to the rotational plane of the propeller. Because of these reasons, it is necessary to know the effect of the oblique flow on the propeller performance. In this paper, the performance characteristics of the counter-rotating propeller were investigated at the different flow angle using numerical and experimental methods.

2. Experimental method

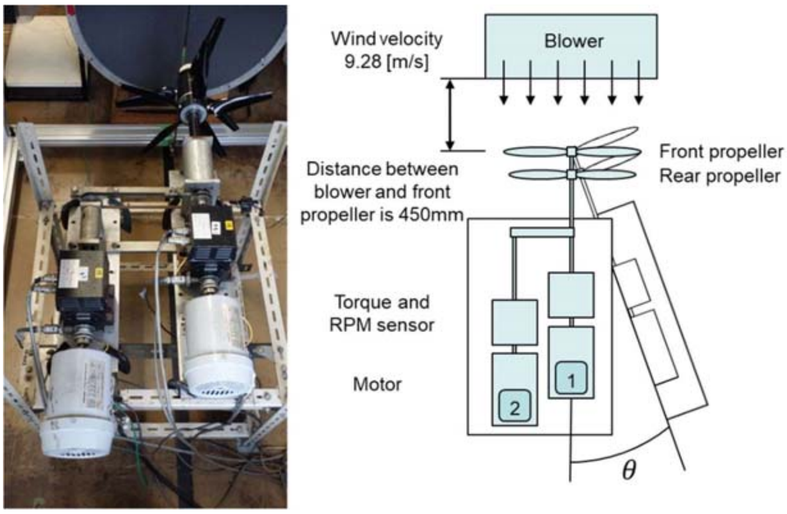


Figure 1. Schematic plan of the counter-rotating turbine experiment device.

A schematic diagram of the experimental apparatus is shown in figure 1. Three blades for the front propeller and five blades for the rear propeller [7] were placed in a 90 mm diameter hub and fixed with a screw nut. The front hub has an elliptical nose cone. The diameters of the front and the rear propellers are 500 mm and 475 mm respectively, and the spacing between propellers is 100 mm.

The front propeller directly drives the motor 1 connected to the inner shaft. The rear propeller drives the motor 2 via a pulley system connected to the external shaft. The two shafts system is equipped with a torque meter and a tachometer, and the two motors are equipped with a regenerative braking system.

The propeller was set at the outlet of the 800mm diameter nozzle in the wind tunnel system, while the wind speed was maintained constant at 9.28 m/s. After setting the rotational torque of the front propeller to match the rotational torque of the rear propeller, the rotational speed and torque were stored in the computer via the data recorder. The rotational torque evaluated without mechanical loss that can be obtained from the bearing and pulley system. As shown in figure 1, the propeller rotation plane can be inclined from 0 to 30 degrees while maintaining the position of the front rotor's center's position.

A torque sensor model SS-050 manufactured by Ono Sokki was used. It has a resolution of 0.001 Nm, an accuracy is ± 0.2% and measuring up to 5 Nm. A Rotational speed sensor model MP-981 manufactured by Ono Sokki was used to measure the rotational speed. It has a measuring range of 0 to 20,000 RPM with ± 0.02% accuracy at full scale. A flow velocity probe TESTO 435 can measure wind speed with an error of ± 1.5% and measured range of 0.6 to 40 m/s.

3. Numerical method

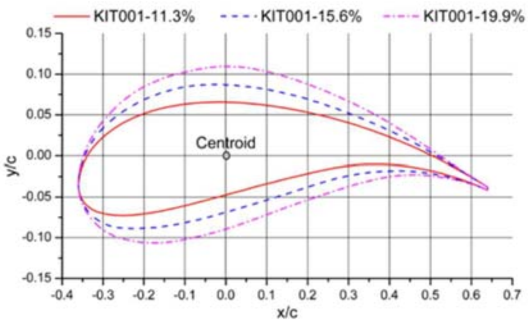


Figure 2. Hydrofoil KIT001 with three different thickness proportions.

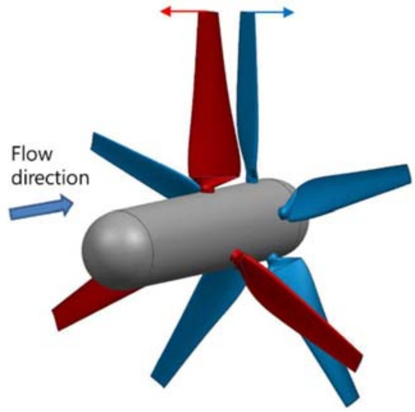


Figure 3. 3D model of counter-rotating tidal stream power unit.

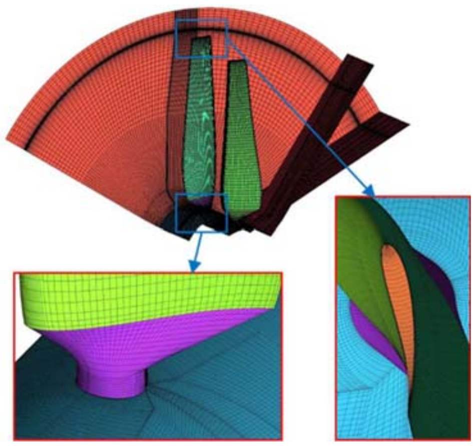


Figure 4. Mesh distribution around the blades.

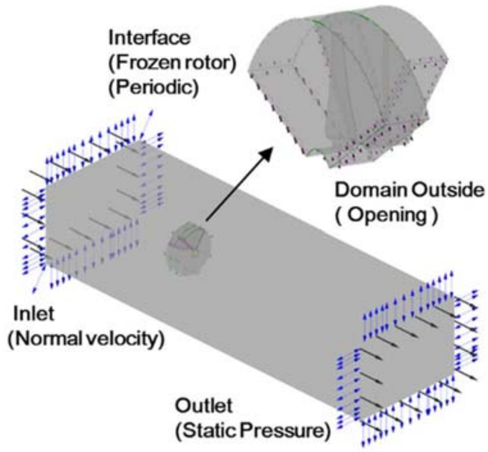


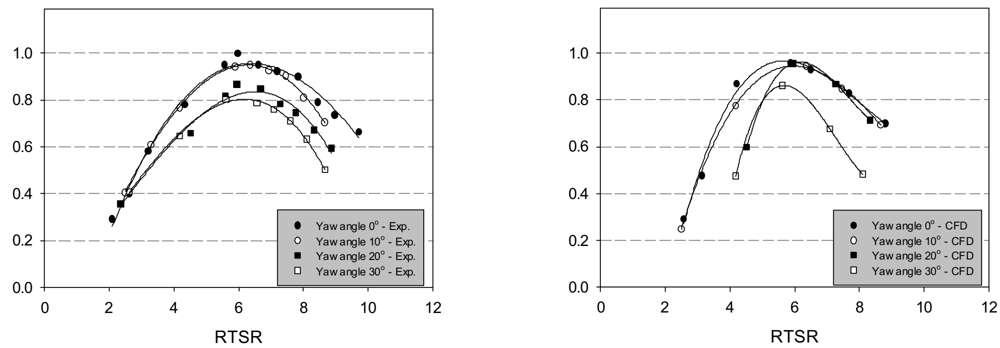
Figure 5. Computational domain and boundary conditions.

Figure 2 shows the in-house hydrofoil KIT 001 used for blade design. Hydrofoils were applied in the radial direction of the blade, the thickness proportions were changed at 11.3%, 15.6% and 19.9%. After being designed by blade element momentum theory (BEMT), the blade profile was optimized by Computational fluid dynamics (CFD) analysis and experiments. The three-dimensional modelling shape of the counter-rotating tidal current turbine is shown in figure 3, where the propeller profiles were described above.

Figure 4 shows a hexahedral mesh used in the simulation generated using ICEM CFD ver 14.5. The total number of nodes is about 2 million. It consists of a total of 3 domains: the front propeller, rear propeller and total flow field. The domain has a length equal to 10 times the diameter of the propeller. For the upstream, set the length three times the diameter, and set the length 7 times the diameter to the downstream. The angle of the front propeller region designated for applying the periodic boundary condition is 120 degrees and the angle of the rear propeller region is 72 degrees. In order to minimize the cost of the simulation, one span in the cascade was used along with a periodic boundary condition.

Figure 5 shows the boundary conditions and calculation domains used for numerical analysis. The inlet has a water velocity of 1 m/s, an angle according to the yaw angle is set, and a static pressure condition is given to the outlet. The boundary between the tandem propeller and the frozen rotor condition is related to the circulation flow condition at the interface of the cascade. The turbulence model was numerically analyzed in the steady state using the k - ω SST (Shear Stress Transport) model.

4. Comparison of results



(a) Experiments. (b) CFD.

Figure 6. Output ratio at different yaw angle.

The power coefficient (CP) and the tip speed ratio (TSR, λ) of the propeller were calculated using the following formula:

$$\lambda_F = \frac{\omega_F R_F}{U} \tag{1}$$

$$\lambda_R = \frac{\omega_R R_R}{U} \tag{2}$$

$$\lambda_T = \lambda_F + \lambda_R \tag{3}$$

$$C_{PF} = \frac{T_F \omega_F}{(1/2)\rho U^3 A} \tag{4}$$

$$C_{PR} = \frac{T_R \omega_R}{(1/2)\rho U^3 A} \tag{5}$$

$$C_{PT} = C_{PF} + C_{PR} \tag{6}$$

$$Output\ ratio = \frac{C_P}{C_{P\ reference}} \tag{7}$$

Figure 6 (a) shows the output ratio according to the yawing angle in the experiment. The highest efficiency point at 0 degrees was set as the reference value of the output ratio. The maximum output ratio at yaw angle of 10 degrees is 0.95 at TSR=6.36, and at 20 degrees it is 0.87 for TSR=5.94, and yaw angle of 30 degree is 0.80 at TSR 5.62. When the yaw angle 10 degrees has a 5% lower output compared with 0 degrees, the yaw angle 20 degrees has a 13% lower output, and the 30 degrees yaw angle has a 20% lower output. The output ratio shows a significant decrease for yaw angles higher than 10 degrees. Regardless of the yaw angle, the maximum output is displayed when the TSR is around 6.36. The decrease in the output ratio at the low TSR is higher than the high TSR. The maximum output is almost constant when the rotational speed changes. even if the rotor inclines, but the output deteriorates with increases of the yaw angle.

Figure 6 (b) shows the result of the CFD analysis. The maximum output ratio is 0.95 at TSR 6.35 when the yaw angle is 10 degrees, 0.96 at TSR 5.94 when the yaw angle is 20 degrees, and 0.86 at TSR 5.62 when the yaw angle is 30 degrees. When the angle is 10 degrees and 20 degrees, the ratio shows a small decrease of 4% and 5%, but when the angle is 30 degrees, it decreases by 14%. The CFD also shows that the maximum output does not vary with the relative rotational speed. In CFD results, when yaw angle after 20 degrees the output ratio shows a significant decrease. Comparing the results, the experiment and the CFD result are in good agreement at the yaw angle of 0 degrees and 10 degrees. However, at 20 and 30 degrees, it is found that the value of the CFD result shows a decrease in experiment and other output ratio. On the other hand, it seems that more detailed cause analysis is required.

5. Concluding remark

In the experiment, the decrease in the output ratio is small at the yaw angle of 10 degrees, but decreases drastically for values higher than 20 degrees. However, in the CFD analysis, a large decrease in the output ratio occurs after the yaw angle of 20 degrees. The CFD analysis result after the yaw angle of 20 degrees slightly differs from the experimental result. In future research, it is necessary to analyze the difference between the experiment and CFD results. Then we need to investigate the performance characteristics as a function of yaw through unsteady analysis in more detail. Analysis of the flow between the front and the rear propeller is necessary.

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