Experiments on the magnetic coupling in a small scale counter rotating marine current turbine

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Abstract. Modern economies are dependent on energy consumption to ensure growth or sustainable development. Renewable energy sources provide a source of energy that can provide energy security and is renewable. Tidal energy is more predictable than other sources or renewable energy like the sun or wind. Horizontal axis marine current turbines are currently the most advanced and commercially feasible option for tidal current convertors. A dual rotor turbine is theoretically able to produce more power than a single rotor turbine at the same fluid velocity. Previous experiments for a counter rotating dual rotor horizontal axis marine current turbine used a mechanical oil seal coupling that caused mechanical losses when water entered through small gaps at the shaft. A new magnetic coupling assembly eliminates the need for a shaft to connect physically with the internal mechanisms and is water tight. This reduces mechanical losses in the system and the effect on the dual rotor performance is presented in this paper.

1. Introduction
Modern economies are dependent on the use of energy in its numerous forms to drive and sustain growth. Whether to provide sufficient heating to its citizens, fuels for transportation or electricity for utilities and vital services, enough energy must be supplied to meet demand. Demand that only increase annually as the population grows. Using energy efficient devices and reducing unnecessary use is one way of reducing demand but more often than not, more fuel is imported to satisfy energy demand. This situation causes dependence on outside sources for supply and concern for energy security. Countries are now considering renewable energy sources, such as the sun, wind and ocean, as alternative and domestic sources of energy. Since these resources are replenished naturally and obtained locally, there are long term benefits of developing infrastructure and technology in for these sources. South Korea is highly dependent on petroleum, coal and liquefied natural gas (LNG) imports to keep up with energy demand. In the government’s National Energy Master Plan [1], it has planned to reduce these imports gradually and amongst other things, to have new and renewable energy resources produce 11% of the energy demand by 2030.

The ocean and all the natural process that occur in it are the result of the solar energy that is radiated by the sun. The solar energy drives the temperature gradients in the sea, the winds over the waters and indirectly drives the waves and currents. Energy that is contained in ocean waves and currents can be
broadly classified under wave energy and tidal energy respectively. Tidal energy sources have the advantage of being more predictable than other sources of energy such as solar or wind. Tidal energy sources can be further divided into tidal range energy and tidal/marine current energy. Tidal range technologies use the differences in water elevation that are caused by high and low tides to drive hydraulic turbines. Whereas marine current energy convertors use the kinetic energy contained in currents to produce power by turbines or an appropriate mechanism [2]. Among the technologies available in marine current energy, the most advanced is the horizontal axis tidal current turbine.

The horizontal axis tidal current turbine utilizes the same principles as a wind turbine with the same orientation and the advances made in the wind industry have also benefitted the marine current turbine designs. In Betz theorem, the theoretical maximum efficiency that can be produce by a single rotor is 59.3% and by extending this theorem to a dual rotor concept, the maximum that can produced is 64% [3]. Lee et al [4] designs a counter rotating turbine that is based on the Blade Element Momentum Theory (BEMT) and investigates the effect of the distance between the two rotors on the performance of the turbine. This present study utilizes a small scale dual rotor horizontal axis marine current turbine design that gives the highest power coefficient from Lee’s study. In addition to this, a new magnetic watertight coupling mechanism is placed at the hub of the counter rotating turbine instead of a mechanical oil seal type coupling system used in the previous study. The new coupling mechanism prevents water from entering the hub and causing mechanical losses. In order to assess the effect the new coupling system had on the performance of the dual rotor turbine, experiments were done on the turbine with the new setup and the results are presented in this paper. Also, the experimental results are also compared to the CFD results obtained in the previous study.

2. Experimental Setup

The experiments were done in a vertically circulating water tank in Korea Maritime and Ocean University. The water tank is 4m in length, 1.8m wide and 1.2m high. The depth of the water used was 0.9m. Before conducting experiments, the water velocity was measured at 15 different equidistant points in plane 1m in front of the turbine. At each point, 5 measurements were taken over a 1 minute duration. The average difference in measures was found to be 2%. The water velocity is controlled by the rotational speed of 2 fans in the tank, which is controlled via control panel. In addition, the water velocity could only be changed from 0.8m/s to 1.4m/s. Over this limit would put the structural integrity of the water tank at risk.

![Figure 1. Diagram of experimental setup with experiment equipment highlighted.](image)

The experimental setup is shown the figure 1 below. The torque meter (model SBB) could measure from 0-2 kgfm. An RPM sensor is also contained in the torque meter and could measure up 10,000 RPM. To control the RPM of the turbine, a forced air cooled type powder brake (model PRB-5Y3F) range.
The water velocity is controlled by a fan via control panel and varied from 0.6m/s to 1.3m/s. The torque, RPM and water velocities are measured and then recorded into a data logger. The blockage ratio of the experimental setup was calculated to be about 12% and a blockage correction factor was used to correct the results [5]. The turbine was located 350mm below the free surface.

The counter rotating turbine contains two rotors of 3 blades each. The blades were designed using the BEMT methodology. The BEMT combines the equations of momentum theory and blade element theory equations to predict the forces that act on a 2D airfoil or 3D blade span. By using the BEMT equations and 2D airfoil data, a rotor blade profile can be designed. The airfoil used for the blade profile was NACA-63421 with different chord lengths and twist angles [4]. The diameter of the model turbine was 500mm, and the distance between the two rotors was 250mm. Furthermore, the blade angle on both the front and rear blades was set at 0°.

![Figure 2.](image)

**Figure 2.** (a) Photo of the Mechanical Oil Seal Assembly (b) Magnetic coupling assembly (c) 3D rendering of the Magnetic coupling.

The mechanical oil seal coupling assembly, magnetic coupling assembly and 3d model of the magnetic coupling is shown in figure 2a-c. Figure 2a shows the mechanical oil seal coupling assembly with the various hub connections and key and shaft design. During earlier experiments, it was observed
that water would leak through small openings between the shaft and the hub and cause friction in the internal gearing. Figure 2b shows the new magnetic coupling assembly and figure 2c is the 3D rendering of the magnetic assembly. The external casing of the magnetic coupling is connected to the rotating blades by a shaft seen in the photo of the magnetic coupling assembly. The external casing closely fits and rotates over the fixed watertight seal/wall. This seal prevents any water from entering the internal portion of the hub. The internal shaft also fits a close fit inside the seal and a bearing inside seal ensures the smooth rotation of the internal shaft. As the external casing rotates over the seal, the magnetic attraction between the magnets of the external casing and internal shaft causes the internal shaft to rotate together with the external casing. In the mechanical oil seal design, the shaft has to connect through to internal gearing and a small gap between the shaft and hub casing must be made to accommodate the shaft. The main advantage of the magnetic coupling is that the new method does not require the shaft to physically connect external and internal portions and thus becomes water tight. This will eliminate potential mechanical losses caused by any water leakage through the shaft opening. This could possibly reduce manufacturing costs and potentially reduce maintenance costs due to fewer parts.

3. Results and Discussion

Figure 3 shows the power output obtained from the experiments of the magnetic and mechanical coupling setups. These results are also compared with results obtained from numerical simulations, labelled as CFD, from the previous study. The maximum power output from the previous experiment was 116.6 W and with the magnetic coupling, the maximum power output was 122.84 W. Both the oil seal coupling and magnetic coupling setups show close agreement with the CFD results. However, the magnetic coupling setup shows a higher output than the oil seal setup. From this graph a small difference can be seen and in order to further study the difference, the mechanical losses caused by both setups can be measured. To measure the overall mechanical loss in the two setups, the water tank was fully drained and the powder brake was removed. The torque/RPM meter was rotated at different rotational speeds and the output torque was measured and averaged.

![Graph of the power output against water velocity. Comparing the Oil Seal, Magnetic coupling and CFD results.](image)

Figure 3. Graph of the power output against water velocity. Comparing the Oil Seal, Magnetic coupling and CFD results.

The difference in overall mechanical loss in torque at different rotational speeds were recorded and presented in figure 4. The figure shows that at all rotational speeds, the averaged mechanical losses that occur in the magnetic coupling setup are lower than the mechanical oil seal setup. The average mechanical loss was 0.035 kgf.m for the oil seal setup and 0.029 kgf.m for the magnetic seal setup. The
difference in losses can be also seen by comparing the effectiveness of the new assembly to the previous one.

![Torque mechanical loss measured for both coupling systems.](image)

**Figure 4:** Torque mechanical loss measured for both coupling systems.

In figure 5, the coefficient of power ($C_p$) calculated for the o ring and magnetic coupling setups are plotted against water velocity. These experimental results are also compared with the numerical result. The coefficient of power is defined as the ratio between the power produced at the turbine and the power available in the water current as shown in equation (1):

$$C_p = \frac{\tau}{0.5 \rho A V_\infty^3} \cdot \frac{2\pi n}{60}$$  \hfill (1)

Where:
- $\tau$ is the torque measured [N.m]
- $n$ is the rotational speed of the turbine [RPM]
- $\rho$ is the density of the water [kg.m$^{-3}$]
- $A$ is the frontal area of the turbine [m$^2$]
- $V_\infty$ is the free stream velocity of the water [m.s$^{-1}$]

The values calculated from magnetic coupling case show better agreement than the oil seal coupling case. The maximum $C_p$ of the oil seal setup was 0.45 at a water velocity of 1.15 m/s and 0.46 for the magnetic coupling setup at a water velocity of 1.24 m/s. The differences caused by the mechanical losses in the oil seal coupling can be observed to have an effect on how efficient the turbine can produce power. By eliminating potential mechanical losses caused by water leakage, the power produced and the effectiveness of the dual rotor turbine is seen to increase. This small improvement in performance would be more apparent and beneficial for larger turbines designed in the kilo-megawatt range.
4. Conclusion
In this study, a magnetic hub coupling design for a dual rotor horizontal axis marine current turbine was tested in small scale experiments. The magnetic design was compared to the mechanical oil seal design of previous studies on the same turbine. In addition, the results were compared with the numerical results of a CFD analysis of the turbine. The best turbine operating parameters according to previous studies such as blade angle and blade gap distance were set at 0° and 250mm, respectively. The magnetic coupling setup showed an increase in power output, lower mechanical losses in torque and higher power coefficient than the oil seal setup. The magnetic coupling case was also in close agreement with the CFD results. The small improvement seen in the small scale experiment could be more apparent and beneficial for larger designs of marine current turbines.

Acknowledgments
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Figure 5: Graph of the CP against water velocity for the Oil seal assembly, Magnetic coupling assembly and CFD results