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Whale Inspired Blade Design of a Contra-Rotating Tidal Turbine

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ABSTRACT

Today, as a rapidly expanding industry within the energy sector, sustainable energy generation through renewable sources such as tidal power creates the potential to get into previously untapped resources. This paper focused on designing, simulating, and analyzing a single rotor tidal turbine and contra-rotating (double rotor) tidal turbine with traditional blade designs and whale-inspired blade designs by using computational analysis. A contra-rotating tidal turbine has a lot of advantages such as near zero reactive torque on the support structure, near-zero swirls in the wake, and high relative inter-rotor rotational speeds. Contra-rotating turbines have capabilities of harvesting higher energy by eliminating the swirling velocity component in the wake as results from the numerical analysis models. Numerical flow visualization proved that the wake verified the reduction of swirl behind the turbine and as expected, the contra-rotating with whale tip blades turbine works best at high tip speed ratios. The high tip ratio values for a contra-rotating turbines has the highest value for a blade with modifications based on whale flippers.

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INTRODUCTION

Recently, due to high oil prices and environmental pollution issues, interest in the development of alternative energy and related research has tremendously increased. Renewable energy, one form of an alternative energy, utilizes energy that can be re-used, as its mechanical power source. Among the many types of renewable energy, tidal stream energy has many attractive features and is known as one of the most promising energy resources. Besides, it is also reliable, foreseeable and has the possibility to minimize both visual and noise pollution.

Originally, tidal energy is the energy dissipated by tidal movements, which occurred by the gravitational and centrifugal forces between the earth, moon and sun: Owen, A., & Trevor, M. (2008). The rotation of the earth and moon produced the rise and fall of the surface of the ocean by gravitational force and named as a tide: Mazumder, R., & Arima, M. (2005).

Another alternative to fossil fuels which are being globalized nowadays is tidal power. However, we still required a more efficiently engineering innovation method to convert tidal energy into a useful form. Humpback whales shown in Figure 1 is not just an endangered species, it also possess evolutionary aerodynamic advantages that are recently being studied. The bumps on their fins' leading edges creating downwind turbulence and it reduces stalling by keeping layers of flow attached to the top of the airfoil at higher angles of attack. Airfoil stalling occurs once the angle of attack surpasses the critical angle of attack. The turbulent flow which is separated is dominant over the attached flow and increases with drag at higher angles of attack. It results in a decrease in lift. Initial research suggests, "turbines fitted with tubercles to the leading edges of each blade are able to produce more power at low fluid speeds, quieter, and perform much better in turbulent fluid streams": Loz, & Blain. (2008).

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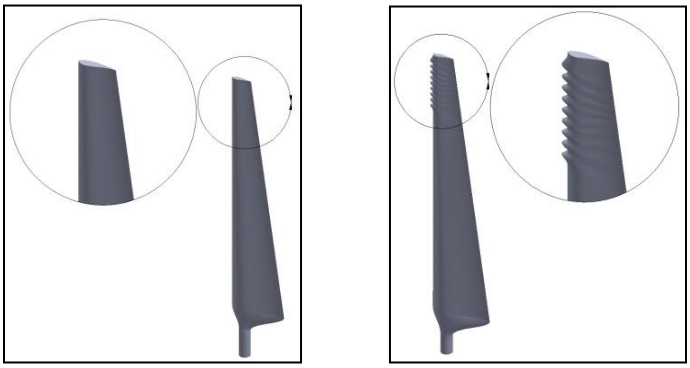
Fig. 1: The humpback whales' flippers: Canter, N. (2008).



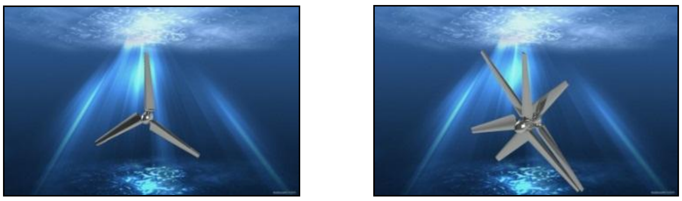
(a) (b)

Fig. 2: (a) Traditional blade and (b) Whale tip blade.

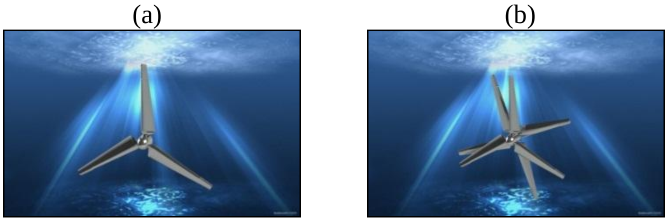
As shown in Figure 2, the whale-inspired turbine blades protrusions or bumps placed on airfoils act as vortex generators. An increase in inertia of the boundary layer fluid flow separation, which caused by the vortices, will root into the delay in stall. Surface protrusions have shown an improvement in aerodynamics such as winglets: Ibrahim, S.Z. et al. (2013) and even small high precision engineering parts: Ibrahim, M.D. et al. (2012, 2013). There is a possibility that at high angles of attack, with the help of these vortex generators of protrusions, can be used to reattach flow to increase the lift.

1. Turbine Blade Design:

In this paper, there are four types of tidal turbine that was modeled using commercialized 3D mechanical CAD program software, SolidWorks. The models are single rotor tidal turbine, contra-rotating tidal turbine: Clarke, J., Connor, G., Grant, A., & Johnstone, C. M. (2007), single rotor whale tip blade tidal turbine and contra-rotating whale tip blade tidal turbine, consecutively shown in Figure 3.



(a) (b)



(c) (d)

Fig. 3: (a) Single rotor tidal turbine, (b) contra-rotating tidal turbine, (c) single rotor whale tip blade tidal turbine and (d) contra-rotating whale tip blade tidal turbine

2. Rotor Hydrodynamic Design:

In order to predict the geometry of the downstream rotor relative to the specified upstream rotor, an extension of conventional Boundary Element Method (BEM) theory is used. For minimising the stall and dynamic interactions during operation, a dissimilar number of blades shown in Figure 4 are chosen for the two rotors (3 on the upstream rotor, 4 on the downstream rotor). The aerofoil section used for both rotors is the NREL S814: Tangler, J., & Somers, D. (1995), which perform well at moderate Reynolds number and are relatively insensitive to surface imperfections.

(a) (b)

Fig. 4: (a) 3 Blades on the upstream rotor and (b) 4 Blades on the downstream rotor.

3. Rotor Design for Torque Matching:

One of an important factor in tidal turbine design is the Tip Speed Ratio (TSR), λ. TSR refers to the ratio between the speed of the flow and the speed of the tips of the tidal turbine blades. In order to maximize the power output and efficiency of the tidal turbine, one must know the tip speed ratio of the tidal turbine.

A lot of water will pass through the gaps between the blades rather than providing energy to the tidal turbine if the rotor spins too slowly. However, if the blades spin too rapidly, they could create excessive turbulent air or act as a solid wall against the water.

A condition of zero net torque is enforced under all design circumstances, it exerted on each of the two rotors by the flowing stream being equal and opposite. The rotor is designed to produce equal torque and equal axial thrust on each rotor for the condition $\lambda_1=\lambda_2=3$. The design produced is then scrutinised by a different BEM code, which predicted the equal torque condition at $\lambda_1=3$, $\lambda_2=2.875$ with an axial thrust distribution of 51% / 49% for the upstream and downstream rotors respectively: an acceptable validation of the design process.

4. Advantages of a Contra-rotating Turbine over Single Rotor Turbines:

The aim for this section is to describe and share the primary reasons behind these advantages and their benefits to the customer. The main advantages of a contra-rotating turbine are negligible reaction torque on the supporting structure, counter-acting wake swirls from adjacent rotors and high inter-rotor rotational speeds. When the rotors rotate in opposite directions, the reaction torques is produced by both rotors working against each other. The benefits of this characteristic are that there is a reduction in structural fatigue and no energy is wasted trying to negate the reaction torque through other means.

The second bullet-point is that there is a different wake structure created by the turbine, which trails behind the rotor as a result. It could thus reduce the environmental impact of shallow water devices if this wake structure is to be reduced due to seabed degradation in the vicinity of the turbine. A secondary advantage is that tidal stream devices in close proximity to each other, as in tidal farms, would not see as much disruption in performance due to turbulent wake interference.

The third and final advantage is that high relative rotational speeds are achieved, which in turn produces a greater power output. This characteristic also has the added benefit that it decreases the requirement for a gear-train assembly.

5. How Contra-Rotating Turbine Works:

In requirement for the contra-rotating tidal turbine to work, it employed two closely spaced contra rotating rotors, then driving a contra rotating electrical generator. The first rotor has three blades rotating in an anti-clockwise direction while the second rotor, located directly behind the first, has four blades rotating in a clockwise direction.

It increase the relative rotational speed doubles compared with a single rotor turbine, letting the turbine to directly drive a flooded, permanent magnet, contra-rotating generator, without a gearbox. The flooded generator is cooled inertly by water, removing parasitic energy losses associated with gearbox driven water tight active oil based gearbox-generator cooling systems and power absorbing shaft seals.

The magnetic field performs across the rotor and rotating-stator sections of the generator as a “differential” and equally splitting the torque between the rotors. Then, the reactive torque acting on the supporting structure is eliminated allowing the system to be tied rather than rigidly attached to the seabed. This enables the turbine to be organized in shallow water.

Figure 5 shows how the turbine is deployed in water. To achieve neutral buoyancy, buoyancy chambers at the front and rear sections of the nacelle are turned. The turbine is then connected to a tensioned mooring at a point in the water column where the flow velocity is utmost and surface wave action lessened. As a result in maximum energy capture, tidal flow induced drag forces ensure that the turbine remains perpendicular to the flow at all states of the tidal diamond, resulting.

The anti-tangled device: *Anti-tangle device*. (2012), is a component to lessen the chance of mooring lines becoming entangled and particularly electrical cables becoming frequently wrapped around other components due to the rotation of the device. The depth of the turbine and the buoy differ as a function of the flow velocity, since the drag forces increase as the flow velocity rises. Thus, the height of the turbine differs over both the diurnal and bi-monthly tidal cycles. However, the flow velocity is a function of depth, due to the variation in the vertical velocity profile. Therefore the turbine height and the flow velocity the turbine experiences are inter-reliant.

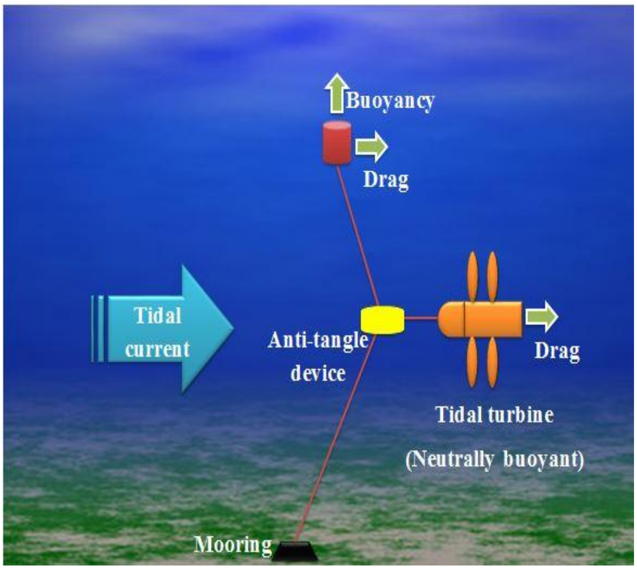


Fig. 5: Flexible mooring for tidal turbine.

RESULT AND DISCUSSION

The commercialized 3D mechanical CAD program software have fully embedded with flow simulation program software where it intuitive CFD tool, SolidWorks Flow Simulation enables to simulate and analyze the model of tidal turbines. The parameter of all turbines is same, which are; the blades rotate at 10 rpm and the velocity of the water is being set at 0.8 m/s.

Extracting energy from flowing water involves much the same physical principles as have been well established for extracting the energy from wind by using wind turbines. The water current kinetic energy resource is determined by the speed and cross-section of flow that can be intercepted. The basic equation for instantaneous power availability is;

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

Where:

A = the swept area of the turbine (m^2)

V = velocity of sea water (m/s)

ρ = density of sea water (1025kg/m^3)

7. Velocity and Wake of the Flow:

An isolated turbine produces power by retarding the flow, which passes through it as a concept. Delaying the flow causes a wake behind the turbine, which widens and ultimately mixes with the flow, which has passed around the turbine.

The simulation analysis results show that there is a dissimilar wake structure created by the turbine, which trails behind the rotor. It could reduce the environmental impact of shallow water devices due to seabed degradation in the vicinity of the turbine if this wake structure is to be condensed. Flow visualization of the wake verified the lack of swirl behind the turbine.

(a) Single Rotor Tidal Turbine:

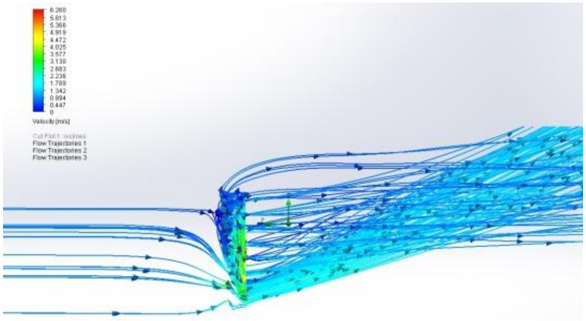


Fig. 5: The velocity and wake of the single rotor tidal turbine (side view).

It is well known that a wake will develop downstream of a tidal stream turbine due to extraction of axial momentum across the rotor plane. Figure 5.0 shows the wake of the flow behind the single rotor tidal turbine. The flow is laminar and smooth but most of the flow moves upward after it passes through the tidal turbine. This will cause the tidal turbine in unbalance position since it connected to a tensioned mooring at a point in the water column.

Table 1: The average velocity of the single rotor tidal turbine.

Av Velocity 1 (m/s)	1.337
Av Velocity 2 (m/s)	1.109
Av Velocity 3 (m/s)	0.140

Extracting energy from the flow creates a region, known as the wake, with reduced velocity behind the turbine. Based on Table 1, the average velocity of water through turbine is 1.337 m/s and the average velocity of tip of front rotor turbine is 1.109 m/s. It shows that the velocity of the flow is reduced after it passes through the tip of front rotor turbine.

(b) Contra-Rotating Tidal Turbine:

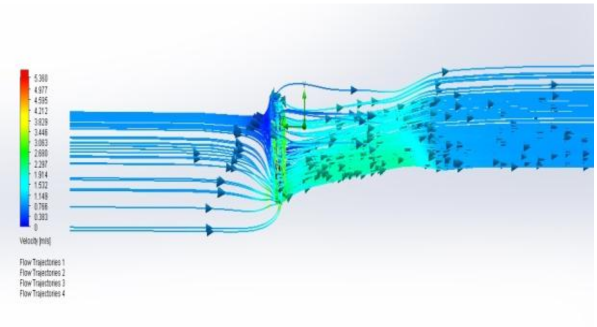


Fig. 6: The velocity and wake of the contra-rotating tidal turbine (side view).

The contra-rotating tidal turbine produces a smooth and laminar wake shown in Figure 6. The green and light blue region shows that the contra-rotating tidal turbine produced a high velocity of wake in big region.

Table 2: The average velocity of the contra-rotating tidal turbine.

Av Velocity 1 (m/s)	1.155
Av Velocity 2 (m/s)	1.109
Av Velocity 3 (m/s)	0.139
Av Velocity 4 (m/s)	1.109
Av Velocity 5 (m/s)	0.140

The average velocity of water through turbine is 1.155 m/s which are lower than the average velocity of water through single rotor tidal turbine. While, the average velocity of tip of front and rear rotor turbine is 1.109 m/s which are same with the average velocity of tip of front rotor of single rotor tidal turbine. This shows that the velocity of the turbine is same even though the number of blade is different.

(c) Single Rotor Whale Tip Blade Tidal Turbine:

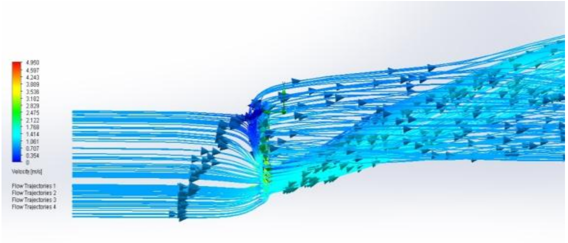


Fig. 7: The velocity and wake of the single rotor whale tip blade tidal turbine (side view).

The single rotor whale tip blade tidal turbine produce laminar flow but the light blue region of wake produced is in a big region. The wake is spread upward after it hit the lower side of the tip blade tidal turbine. This will cause the tidal turbine in unbalance position.

Table 3: The average velocity of the single rotor whale tip blade tidal turbine.

Av Velocity 1 (m/s)	1.390
Av Velocity 2 (m/s)	1.133
Av Velocity 3 (m/s)	1.059

The average velocity of water through the single rotor whale tip blade tidal turbine (1.390 m/s) is higher than the single rotor tidal turbine and contra-rotating tidal turbine. This show that the blade of this tidal turbine rotate faster than the other two turbines.

(d) Contra-Rotating Whale Tip Blade Tidal Turbine:

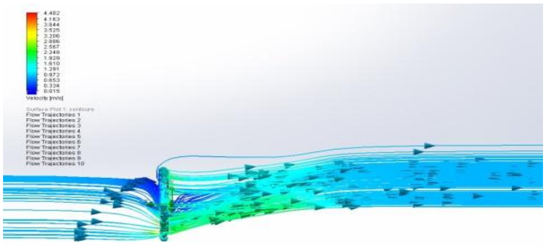


Fig. 8: The velocity and wake of the contra-rotating whale tip blade tidal turbine *(side view).*

Figure 8 shows a smooth and laminar flow of the wake behind the contra-rotating whale tip blade tidal turbine. The wakes produced were smaller than the contra-rotating tidal turbine. These reduce the environmental impact of shallow water devices due to seabed degradation in the vicinity of the turbine.

Table 4: The average velocity of the contra-rotating whale tip blade tidal turbine.

Av Velocity 1 (m/s)	0.134
Av Velocity 2 (m/s)	1.059
Av Velocity 3 (m/s)	1.057
Av Velocity 4 (m/s)	0.133
Av Velocity 5 (m/s)	1.305

The average velocity of tip of front and rear rotor turbine is 1.059 m/s and 0.133 m/s respectively. It shows that the whale tip blade had given effect to the velocity of the turbine.

Based on Figure 5.0, 5.1, 5.2 and 5.3, all the tidal turbines produce smooth and laminar flow. Both of contra-rotating tidal turbines (traditional blade and whale tip blade) show a better wake reduction than single rotor turbines. But by referring the velocity of the fluid flow behind the turbine, the contra-rotating tidal turbine produce higher impact of wake than contra-rotating whale tip blade tidal turbine. In other words, the contra-rotating whale tip blade tidal turbine is near-zero swirl in the wake of the turbine, reducing scouring of the seabed downstream.

Figure 9 shows that the velocity of the wake flows behind the tidal turbines. The single rotor tidal turbine has a highest velocity while contra-rotating whale tip blade tidal turbine has the lowest velocity of the wake flow. This means that the single rotor tidal turbine has the highest impact towards natural life while contra-rotating whale tip blade tidal turbine lowest. Numerical flow visualization of the wake verified the lack of swirl behind the turbine.

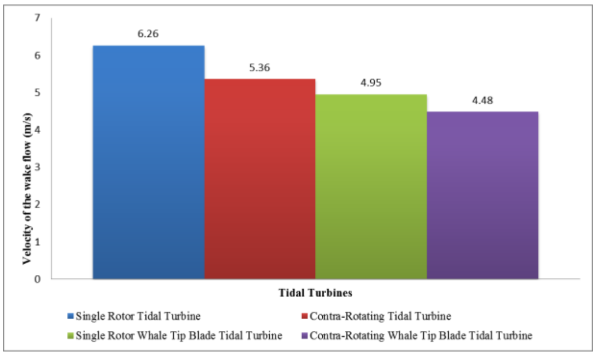


Fig. 9: The velocity of the wake flow VS tidal turbines.

The turbine design incorporates two co-axial rotors that rotate in opposite directions. Hence, the results in near-zero reaction torque on the supporting structure and mooring with the desirable side-effect of a decrease in turbulent wake and potentially reducing the environmental impact as well as increasing the power output of the device, which will be explained in details in the next sub-section 8.

8. Power Coefficient:

The power coefficient, CP is an examination of one of the simplest and most commonly used ways to analyse the aerodynamic performance of airfoil sections. The total difference between the coefficients of the upper and lower side of the airfoil can give a signal of aerodynamic efficiency of the blade.

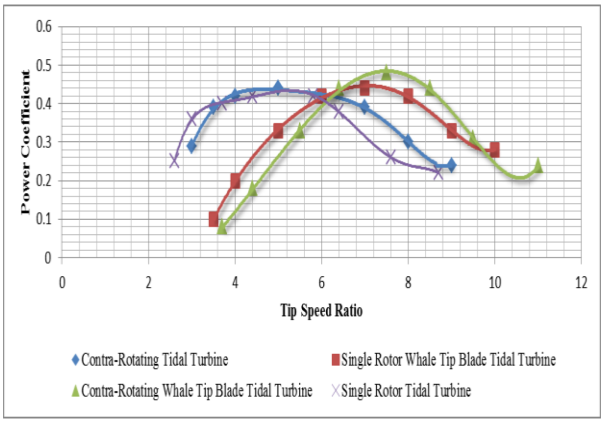


Fig. 10: Power Coefficient VS tip speed ratio.

Based on Figure 10, the contra-rotating whale tip blade is proficient of having a higher power coefficient by removing the swirling velocity component in the wake. The peak values of CP of single rotor tidal turbine and single rotor whale tip blade tidal turbine are parallel. The contra-rotating whale tip blade tidal turbine works best at high tip speed ratios as predictable. Its peak thrust coefficient higher that others tidal turbine.

The maximum power extraction occurs at the optimal tip speed ratio. This is due to the maximum turbine power coefficient in all tests at 0.8 m/s towing speed was 0.48 at a tip speed ratio of about 7. This show that The NREL S814: Tangler, J., & Somers, D. (1995), has less drop in power coefficient as the pitch angle is changed making it the better performer in terms of both performance indicators.

9. Conclusion and Future Recommendations:

Based on the simulation of the models, it showed that a contra-rotating whale tip blade tidal turbine with near-zero reactive torque on the support structure, near-zero swirl in the wake, and high relative inter-rotor rotational speeds can be operated magnificently.

In order to allow easy optimisation of a contra-rotating rotor and further analysis of the wake structure at this optimised configuration, a further study that includes a systematic investigation of the effects of inter-rotor spacing, and a comprehensive analysis of dynamic blade loads should be done. These model studies of mooring should be measured as important to simplify structural design which will achieve near-zero reaction torque on the supporting structure. Continued analysis and testing programme for rotor blade materials to provide structural integrity and resistance to the tough marine environment.

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