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Computational fluid dynamics based performance optimisation of vertical axis marine current turbines.

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Computational Fluid Dynamics based Performance Optimisation of Vertical Axis Marine Current Turbines

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ABSTRACT
Rapid decrease in the fossil fuels in the last couple of decades has stirred the researchers to find alternative sources for the production of power. Wind and tidal energies are the two most promising alternatives to the fossil fuels. While most of the recent research has been conducted on developing electro-mechanical systems for power production from wind energy, the research regarding the use of the tidal energy for power production is severely limited. In the present study, performance characteristics of an in-house built Darrieus type Vertical Axis Marine Current Turbine have been numerically simulated. An effort has been made to analyse and understand of the complex flow phenomenon occurring in the vicinity of such turbine. Furthermore, the optimisation study has been included for various flow configurations. It has been shown that the optimum operating condition of the vertical axis marine current turbine occurs at a tip speed ratio of 0.17 when the power production from the turbine is at its maximum.

Keywords
Vertical Axis Marine Current Turbine, Tip Speed Ratio, Torque Output, Power Output, Computational Fluid Dynamics.

Nomenclature

- r Radius of VAMCT (m)
- v Linear velocity (m/sec)
- ω Angular velocity (rads/sec)
- T Torque Output from VAMCT (N-m)
- P Power Output from VAMCT (W)

1. INTRODUCTION
Marine Current Turbines (MCTs) convert the kinetic energy of the tidal waves into useful energy forms. Two common types of MCTs are Horizontal Axis and Vertical Axis Marine Current Turbines. The principle of operation of both these types is the same as for Horizontal Axis and Vertical Axis Wind Turbines i.e. HAWT and VAWT. The use of Darrieus type Vertical Axis Marine Current Turbines (VAMCTs) provides several advantages over Horizontal Axis Marine Current Turbines (HAMCTs) such as the low starting torque, quite operation and insensitivity to the angle of incident flow. Hence, VAMCTs are better suited to extract power from tidal energy.

Two MCTs of 1 MW capacity were installed in June 2008 by SeaGen in Strangford Narrows, Northern Islands. It has been reported by Dai et. al. [3] that the dominance of the HAMCT over VAMCT is not as pronounced in the hydrokinetic energy generation as it is for wind energy. Researchers have been trying to optimise the performance of VAMCTs by modifying the geometric features of such turbines. Most of the on-going research is benefitting from the commercially available Computational Fluid Dynamics packages in order to analyse the complex fluid flow phenomenon in the vicinity of VAMCTs.

Yang et. al. [7] have numerically simulated a two dimensional Hunter Turbine using CFD and have conducted optimisation studies. They have further carried out laboratory based experiments using Particle Image Velocimetry for various rotor blade configurations [8]. Li et. al [4] have numerically simulated a VAMCT having four rotor blades. Through this study they could understand complex flow phenomena with in rotors. Bai et. al. [1] has used CFD to simulate the effects of an array of VAMCTs in an ocean bed and found effect of arrays on power capture. Paillard et. al. [5] has carried out some preliminary CFD based investigations on a VAMCT. Turnock et. al. [6] has numerically simulated an array of MCTs to analyse the wake of such turbines.

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In the present study a novel in-house built Darrieus type VAMCT has been numerically simulated using a commercial CFD package. The VAMCT consists of 12 rotor and stator blades respectively where the stator blades are flat plates whereas the rotor blades have been curved at 28.2º. Figure 1 shows the geometry of the VAMCT that has been used in the present study.

The important performance parameters of vertical axis turbines, as mentioned by Colley et. al. [2], are the tip speed ratio (TSR) and the torque output. TSR is the ratio between the rotational speed of the tip of the blade and the actual velocity of the wind.

$$\lambda = \frac{r * w}{v} \qquad \text{..……...…...……} \; (1)$$

where r is the radius of the vertical axis turbine, w is the angular velocity and v is the linear velocity. Torque output of the wind turbine has a significant impact on the total power output of the turbine.

$$P = w * T \qquad \text{……..……… (2)}$$

where P is the power and T is the torque output.

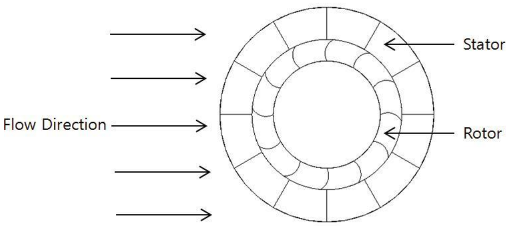

Figure 1. Vertical Axis Martine Current Turbine Model.

2. NUMERICAL MODELLING

The performance output of the VAMCT has been numerically analysed for various flow configurations. These flow configurations correspond to the tip speed ratios of 0.01, 0.05, 0.1, 0.2 and 0.4. A Commercial CFD package has been used to numerically simulate the flow in the vicinity of the VAMCT. The VAMCT has a diameter of 2m and a height of 1m. The geometric details of the flow domain, encompassing the VAMCT, have been shown in figure 2. 1 m/sec of water flow velocity has been specified at the inlet boundary of the domain whereas the outlet of the flow domain is assumed to be at zero gauge pressure. The operating pressure within the flow domain has been specified such that the VAMCT is assumed to be operating at a depth of 1 m below the surface of water. Hence, the operating pressure that has been specified to the solver is 111117 Pa. The sides of the flow domain have been specified as walls with no-slip boundary conditions and moving in the direction of the flow at 1 m/sec such that the generation of the boundary layer at these walls can be neglected. Two equation k-ε turbulence model has been shown to resolve the turbulent parameters in the flow domain with reasonable accuracy [9] and hence has been chosen for analysis in the present study. Sliding mesh technique as mentioned by Park et. al [10] has been used to rotate the blades with respect to the central axis of the turbine.

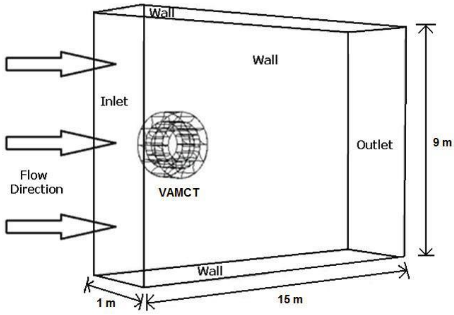

Figure 2. Flow domain encompassing the VAMCT.

Three dimensional unsteady Navier Stokes equations have been numerically solved in an iterative manner to predict the flow structure in the vicinity of the VAMCT for every 3^0 rotation of the rotor blades. During the initial revolutions of the VAWT, significant changes in the flow structure have been observed due to the numerical diffusion. The flow structure within the flow domain has been constantly monitored. The non-uniformities in the predicted flow fields die out from 2^{nd} revolution onwards and hence the solution becomes statistically steady.

3. RESULTS AND ANALYSIS

Numerically converged solutions have been used to analyse the effect of various parameters on the output characteristics of the vertical axis marine current turbine. To ensure that the results obtained are independent of the mesh being used for the analysis purposes, a mesh independence study has been conducted. The results suggests that a mesh of two million elements is capable enough to capture the small scale flow related features with reasonable accuracy and hence has been chosen for analysis in the present study.

3.1 Flow Field Analysis

Figure 3 shows the velocity field in the vicinity of the VAMCT at TSR = 0.01. It can be seen that near the stator blades the velocities are very small because of the no-slip boundary condition. However within the stator blade passages the velocities increase. Within the rotor passages the velocity field is found to be non-uniform. On the rear of the VAMCT, velocities are much smaller as compared to the front end. Similar trends have been found at other TSR values.

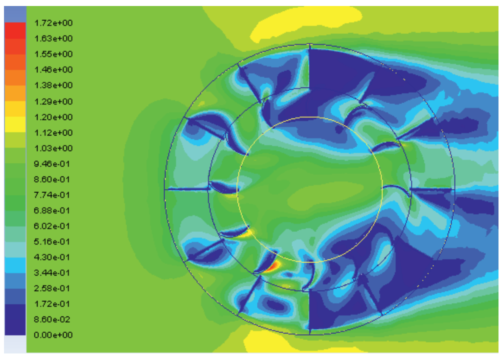

Figure 3. Variations in the Velocity magnitude in the vicinity of the VAMCT at TSR = 0.01.

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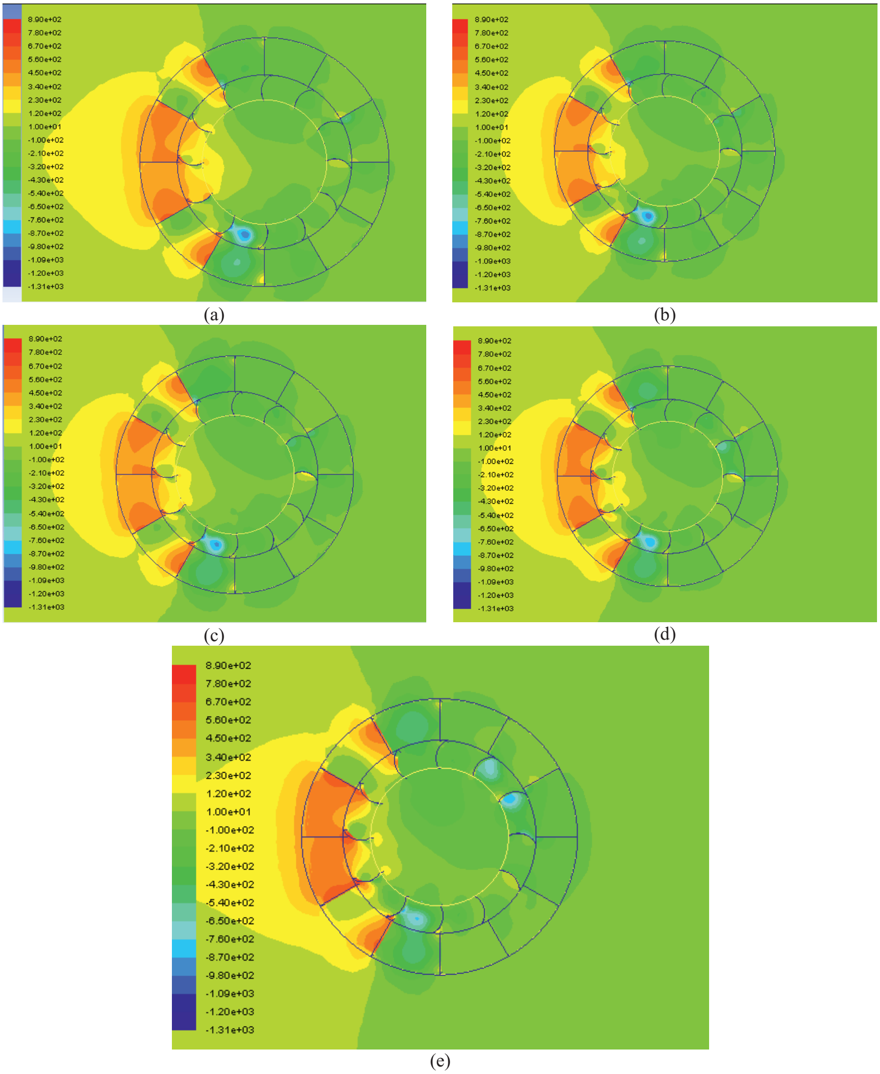
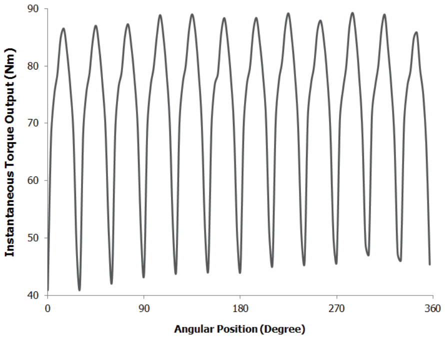


Figure 4. Variations in the Static Pressure in the vicinity of the VAMCT (a) TSR = 0.01 (b) TSR = 0.05 (c) TSR = 0.1 (d) TSR = 0.2 (e) TSR = 0.4.

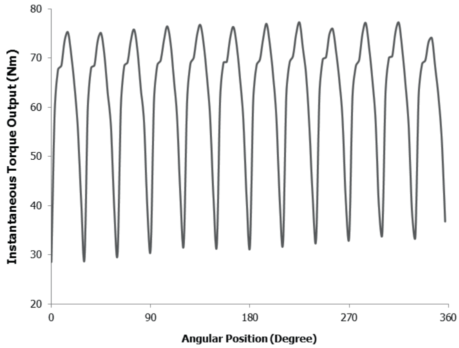
In order to further analyse the flow field in the vicinity of the VAMCT, static pressure distributions for various TSRs have been shown in figure 4. The static pressure contours have been plotted against the same scale for accurate comparison at various TSRs. It can be seen that the areas of high velocities corresponds to low pressures and vice versa. Hence, high pressure region exists at the front end of the VAMCT and a comparatively low pressure region exists at rear end of the VAMCT. Furthermore, the static pressure distribution within the rotor passages and within the core region of the VAMCT is highly non-uniform.

3.2 Performance Characteristics

In order to analyse the performance of the VAMCT, instantaneous torque outputs for various TSRs under consideration have been plotted in figure 5 for one complete revolution of the VAMCT. The results presented here correspond to the third revolution of the VAMCT when the solution has become statistically steady and all the variations in the performance outputs have died out. It can be seen that the torque output from the VAMCT shows a trend of alternative peaks and valleys corresponding to different rotor blades' angular position. The peaks in the outputs are formed when the rotor blades are in-line with the stator blades hence forming large uniform passages for the flow of water. Whereas, the valleys occur when the rotor blades are positioned such that



(a)



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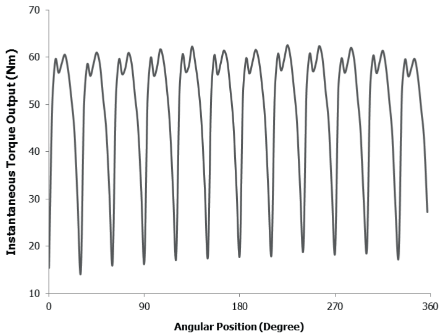

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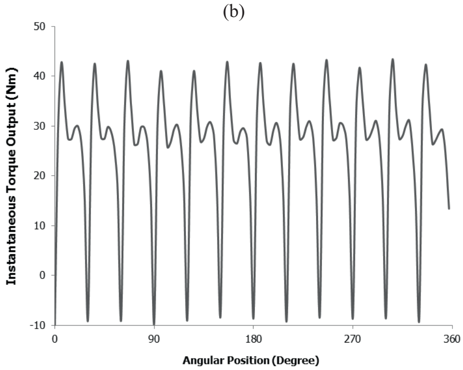
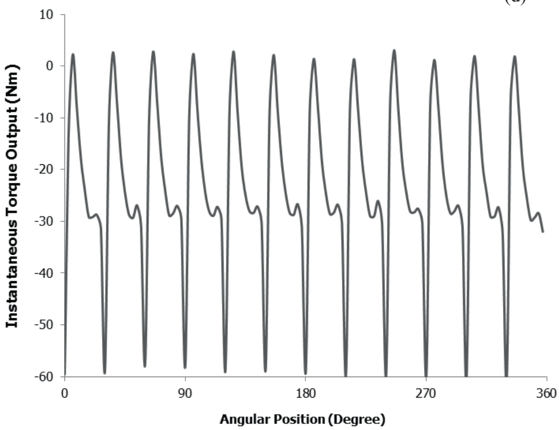


(d)



(e)

Figure 5. Variations in Instantaneous Torque Output in one revolution of the VAMCT (a) TSR = 0.01 (b) TSR = 0.05 (c) TSR = 0.1 (d) TSR = 0.2 (e) TSR = 0.4.

there exists non-uniform passages in the rotor section of the VAMCT, leading to non-uniform pressure distribution around the rotor blades, This leads to vibrations in the VAMCT and hence degrading the structural integrity. It can be clearly seen that as the TSR increases, the torque output decreases. For TSR = 0.4, it is clear from the figure that the torque output is negative.

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The average torque and power outputs for one complete revolution of the VAMCT are shown in table 1. It is evident that as the TSR increases, the power output decreases. For a TSR of 0.4, the power output is negative which means that the VAMCT is in churning condition and the instead of generating power, the VAMCT is actually consuming power. This condition is of no use as far as power generation from VAMCTs is concerned and hence dictates the upper limit of the TSR under investigation.

Table 1. Average Torque and Power outputs at various TSRs

TSR	Average Torque Output (Nm)	Average Power Output (W)
0.01	72.34	1.03
0.05	61.53	4.39
0.1	49.26	7.03
0.2	25.52	7.29
0.4	-23.21	-13.25

With respect to TSR = 0.01, the average torque output decreases by 15%, 32%, 65% and 132% for TSRs of 0.05, 0.1, 0.2 and 0.4 respectively. However, the power output first increases and then decreases for increasing TSR. From TSR = 0.01 to 0.05, the average power output increases by 326%, from TSR = 0.05 to 0.1 by 60% and from TSR = 0.1 to 0.2 by 3.7% respectively. From TSR = 0.2 to 0.4, the average power output from the VAMCT decreases by 281% indicating that the maximum power output lies between TSR = 0.1 and 0.4.

In order to find out the optimal operating condition for the VAMCT that corresponds to the maximum power output, average torque and power outputs for various TSR values have been plotted together in figure 6. Furthermore, angular speed has also been plotted on a separate scale for comparison. It can be seen that at TSR = 0.315 both the average torque and the average power outputs reaches zero values. At TSR higher than 0.315, both the performance outputs of the VAMCT have negative values showing that the VAMCT is in churning condition. The torque curve shows a constantly decreasing trend w.r.t. TSR whereas the angular speed of the VAMCT keeps on increasing for the same incident flow velocity. However, the average power output first increases and then decreases as TSR increases. The peak of the average power output curve lies at a TSR of 0.17 indicating that the optimal operating condition for the VAMCT at 1 m/sec of incident flow of water and operating at 1 m depth corresponds to TSR of 0.17 where the average power output reaches a value of 7.93 W.

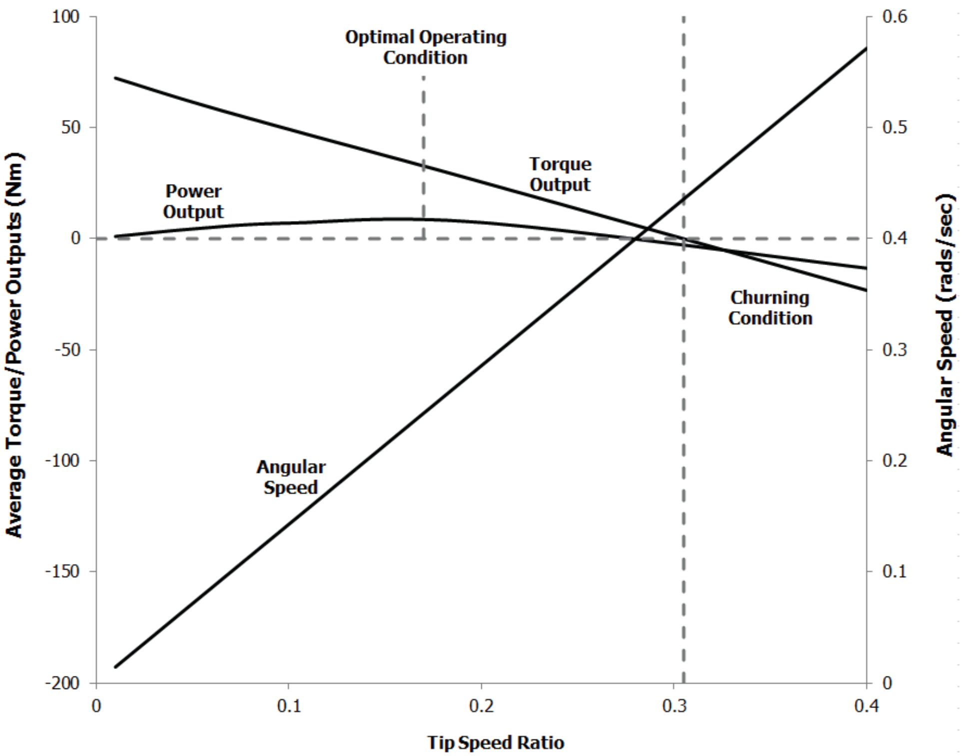

Figure 6. Optimal operating condition of the VAMCT.

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4. CONCLUSIONS

A novel design of a Vertical Axis Martine Current Turbine has been numerically simulated for various Tip Speed Ratios. A detailed analysis of the flow field in the vicinity of the VAMCT has shown the presence of high pressure regions at the front end and low pressure regions at the rear end of the VAMCT. Furthermore, it has been shown that as the TSR increases, the torque output from the VAMCT decreases. However, the average output power first increases until it reaches a value of TSR where the average power output from the VAMCT is maximum. This point is regarded as the optimal operating point for the VAMCT. Further increasing the TSR decreases the average torque output from the VAMCT until it reaches the churning condition. Furthermore, it has been shown that Computational Fluid Dynamics based techniques are capable of accurately predicting the flow field in the vicinity of VAMCTs.

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