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Research Article

Difference between Fixed and Variable Pitch Vertical Axis Tidal Turbine-Using CFD Analysis in CFX

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Abstract: As concerns about rising fossil-fuel prices, energy security and climate-change increase, renewable energy plays a vital role in producing local, clean and inexhaustible energy to supply world rising demand for electricity. In this study, hydrodynamic analysis of vertical axis tidal turbine (both fixed pitch and variable pitch) is numerically analyzed. Two-dimensional numerical modeling and simulation of the unsteady flow through the blades of the turbine is performed using ANSYS CFX, hereafter CFX, which is based on a Reynolds-Averaged Navies-Stokes (RANS) model. A transient simulation is done for fixed pitch and variable pitch vertical axis tidal turbine using a Shear Stress Transport turbulence (SST) scheme. Main hydrodynamic parameters like torque T, combined moment C_M, coefficients of performance C_P and coefficient of torque C_T, etc., are investigated. The modeling and meshing of turbine rotor is performed in ICEM-CFD. Moreover, the difference in meshing scheme between fixed pitch and variable pitch is also mentioned. Mesh motion option is employed for variable pitch turbine. This study is the one part of the ongoing research on turbine design and developments. The numerical simulation results are validated with analytical results performed by Edinburgh design Ltd. The study concludes with a parametric study of turbine performance, comparison between fixed pitch and variable pitch operation for a four-bladed turbine. It is found that for variable pitch we get maximum C_P and peak power at smaller revolution per minute N and tip sped ratio λ.

Keywords: Fixed and variable pitch, simulation, tidal current device, tidal current turbine CFD, tidal energy, Vertical Axis Tidal Turbine (VATT)

INTRODUCTION

Renewable Energy (RE) is a form of energy that can be produced without depleting natural resources such has fossil fuels and wood. It does not rely on the burning of a fossil fuel to create electricity. Because there are little or no fuel costs associated with generating electricity from renewable sources, more researchers are looking to resources like wind, geothermal, hydropower, tides, waves, solar and biomass to hedge against the price volatility of natural gas and diesel. RE facilities generally require less maintenance than traditional generators. Their fuel being derived from natural and available resources reduces the costs of operation. RE projects can also bring economic benefits to many regional areas, as most projects are located away from large urban centers and suburbs of the capital cities. So, it's easy to generate it locally as to avoid the huge cost if supplying from the main distributing power house. For more detail on renewable-energy resources see the review article (Rourke *et al*., 2009; Charlier, 2003). Regarding harnessing the tidal energy 2 main sources are horizontal and vertical axis turbines. This division is based on turbine axis with respect to flow direction. When the flow direction is parallel to the axis of rotation, the turbine is horizontal axis turbine, further detail on this turbine how its work and its numerical and experimental simulation see the reference (Coiro *et al*., 2006; Sun and Zhang, 2010; Batten *et al*., 2007). When the flow direction is perpendicular to the axis of rotation the turbine is a vertical axis. For more detail on the difference between vertical axis and horizontal axis turbine concern the review articles (Shikha *et al*., 2005; Khan *et al*., 2009). In this study, main parameters of fixed pitch and variables pitch VATT are studied using CFX analysis. Also the difference between there working principal is highlighted. Further, the difference between numerical simulation and meshing scheme is also focused. The main drawbacks of fixed pitch are mentioned and how they can be overcome using variable pitch mechanism is studied thoroughly.

METHODOLOGY

Basic principal of vertical axis tidal turbine: The concept of Vertical Axis Tidal Turbine (VATT) is analogous to wind turbines. The attracting feature of

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tidal turbine is that how much energy the turbine will generate for the certain period of time, can be predictable in advance due to the tide data available. VATT consists of a central shaft perpendicular to flow direction. The blades are attached to the shaft via connecting arms. The connecting arms are made of hydrofoil section, which may reduce some resistance and, thereby contributing some net power increase. The blades are usually straight and 2-4 in numbers with NACA0012, NACA0015 and NACA0018 profiles are commonly used (Coiro *et al*., 2006; Sun and Zhang, 2010). Helical and curved blades are also used but in this study NACA0018 straight bladed are used. That's why we not discussed more on Gorlovka Helical Turbine model (Zanette *et al*., 2010; GCK Technology, 2012). Usually, one end of the shaft is connected with generator via a transmission box. The generator converts the kinetic energy into electrical energy. VATT uses the lift force of the incoming flow to generate the torque as oppose to Savories turbine which is drag based. Well-designed Savories turbines generate high torque at low rotational speed. But the coefficient of performance is low as compared to VATT (Golecha *et al*., 2012). Lift type turbines, such as vertical axis Durries turbine, employ aerofoil-section blades to generate lift. These turbines convert this lift into positive torque when their blades are travelling satisfactorily fast relative to the free-stream flow. Such turbines operate at Tip Speed Ratio (TSR, λ), up to approximately 6 and achieve greater efficiencies than drag turbines (Lazauskas and Kirke, 2010). When the rotor rotates, it experiences a changing relative flow, which is the vector sum of local stream flow and the blade's own speed. An angle of attack α is generate in a free stream flow, both the angle of attack of this relative flow and the magnitude of its velocity vary with the orbital position of the foil, called the azimuthally angle (θ). When a blade rotates, its local angle of attack $\boldsymbol{\varphi}$ changes leading to variable hydrodynamic forces. The relation between angle of attack α, local attack angle or blade angle $\boldsymbol{\varphi}$ and azimuthally angle θ is:

$$\alpha = \tan^{-1}\left[\frac{V\cos(\theta+\varphi) - R\omega\sin\varphi}{V\sin(\theta+\varphi) + R\omega\cos\varphi}\right] \tag{1}$$

where,
V: The free stream velocity
R: The radius of turbine
ω: The angular velocity of the turbine

For the fixed pitch turbine, local attack or blade angle ø is zero. During each revolution positive and negative angle of attack form, the resultant hydrodynamic forces acting on the blade has two components, i.e., normal force FN perpendicular to chord and tangential force f_t parallel to the blade chord. Lift force is generated at a small angle of attack has a tangential component in the direction of flow, at this position drag is small; a positive torque is produce by the blades attached to the rotor. This torque is used to drive the turbine. Figure 1 shows a schematic top view of VATT. The blades are mounted on the shaft with three connecting arm. VATT usually operates at small angle of attack (less than 10°). At a higher angle the aerofoil undergoes stall condition i.e., the flow separate from the upper surface of the blade; in this state lift drop and drag increases. More detail can be found in study by Pawsey (2002) on wind turbine. The advantage of VATT (Durries type) is that it does not depend on the flow direction and not need yaw adjustment relative to the flow. The blades can be easily produced due to uniform cross section. Moreover, the generator is attached to the shaft at one side and mostly outside the water making more accessible for maintenance purposes. Mostly, VATT is more suitable for shallow depth. The Main drawback of fixed VATT is in ability to self-start due to a stalled phenomenon of the blades at low and intermediate tip speed ratios and a need arise for variable pitch VATT. Further detail related to stalling condition is available in reference (Kirke and Lazauskas, 2011) and will be discussed in coming sections. To control the blade angle of attack with varying blade pitch angle, two control mechanisms are employed in variable pitch VATT. These are;

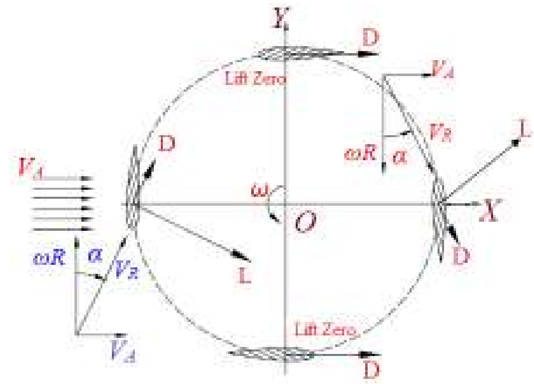

Fig. 1: Working principal of vat

Active variable pitch method: In this mode, a separate actuating device or cam system is used for periodic variation in pitch angle as a function of azimuth angle. This design has been tested by a number of researchers such as McConnell (1979) and Meikle (1993). A simple cam driven system was used by Durries in his patent for fixed pitch turbine. Later (Drees, 1978), developed a similar design called a 'Cycloturbine' for wind turbine. The blade pitch is controlled using a central cam and push rods to each blade. The cam is oriented with the wind direction using a small tail vane. He claims reliable self-starting and a high maximum power coefficient C_p of 0.45 in a test field. Example of Cam control cycle-turbine mechanism is shown in Fig. 2.

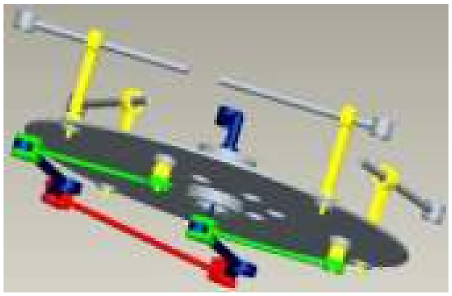

Fig. 2: Active variable pitch control mechanism

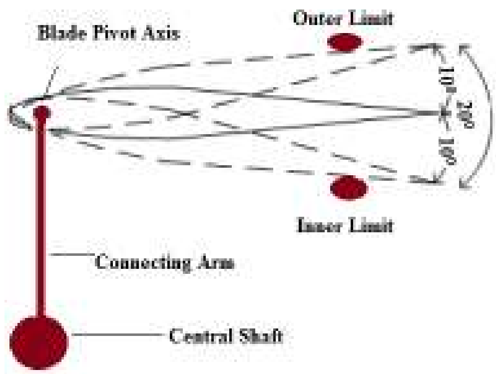

Fig. 3: Variable blade pitch angle position

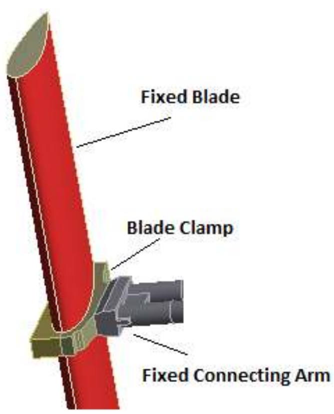

Fig. 4: Fixed blade turbine geometry

Passive variable-pitch method: Since in the active variable pitch, control system or some sensing device is required to sense the current speed relative to rotor speed, this make it complex and limit this mechanism for use water as compared to wind. Some passive techniques include geometric shaping to manipulate relative velocity gradient. Like the blade is free to pitch about a longitudinal axis near the leading edge with a pin and clamp mechanism. The blade is clamped and with pin provided for pitching moment between the blade and connecting arm, the geometry is made such that maximum pitch angle (u_p) provided is from +10º to -100 as shown in the Fig. 3 to 5. Also the difference between the fixed Durries type and passive variable

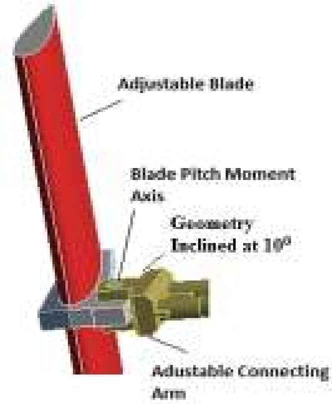

Fig. 5: Passive variable pitch geometry

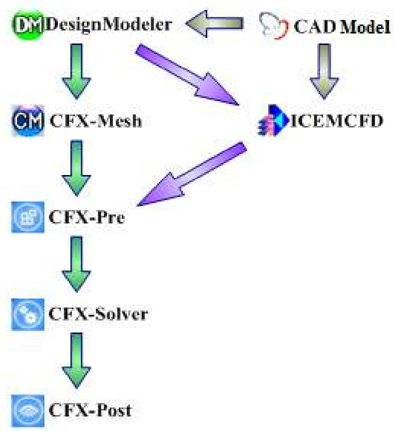

Fig. 6: Scheme of methodology

pitch is shown in Fig. 4 and 5. The exact position of the blade with respect to hinge axis can be known at the equilibrium state between inertial, hydrodynamic and hinge moments. Furthermore, the relation between pitch angles, pitching moment (M_p) is adjusted using Eq. (2) below:

$$I\ddot{\alpha}_p + H\dot{\alpha}_p + K\alpha_p = M_p \tag{2}$$

where,
H: The hinge damping
K: The hinge stiffness
I : The blade moment of inertia about the hinge axis

Further detail on pitching moment is available in article by Salvatore (2012). In this study we will do simulation for fixed blade and passive variable pitch VATT.

RESULTS

Modeling and simulation: The main parameters considered for fixed and variable turbines models are: Number of blade's N = 4, Blade chord length C = 0.6 m, Blade airfoil: NACA 0018, Blade span or height H = 5.5 m, Diameter of rotor D = 4 m. The scheme of methodology opted is shown below in Fig. 6. The analysis presented in this study has been performed using the commercially available software ANSYS CFX-13. CFX is based on RANS mass & momentum equations as discussed above, due to hybrid topology of finite volume and finite difference discretezation methods it can solve any mesh topology. ICEM CFD is used to model a rotor and stator field. Multi-domain grid scheme is used in which inner domain rotates and the outer domain is stationary. The hydrofoil mesh is done by grid stretching. Inlet Boundary Condition (BC) is applied at the left side of outer domain with free stream velocity of up to 3.5 m/s with turbulence option of medium intensity 5%. BC at outlet and sides are considered with opening to avoid the wall effects. For inner rotating domain each blade is separately considered and analyzed with mass and momentum option of no slip at the wall. The no-slip condition is by default and it indicates that the fluid sticks to the wall and moves with the same velocity as the wall, as in this case, blade rotates. The interface is applied where the outer and rotating domain meet each other. Both the models are solved with option of A Shear Stress Transport (SST) model. In the case of a fixed blade only 2 mesh regions are generated 1 for the outer domain and one for the rotating domain containing the

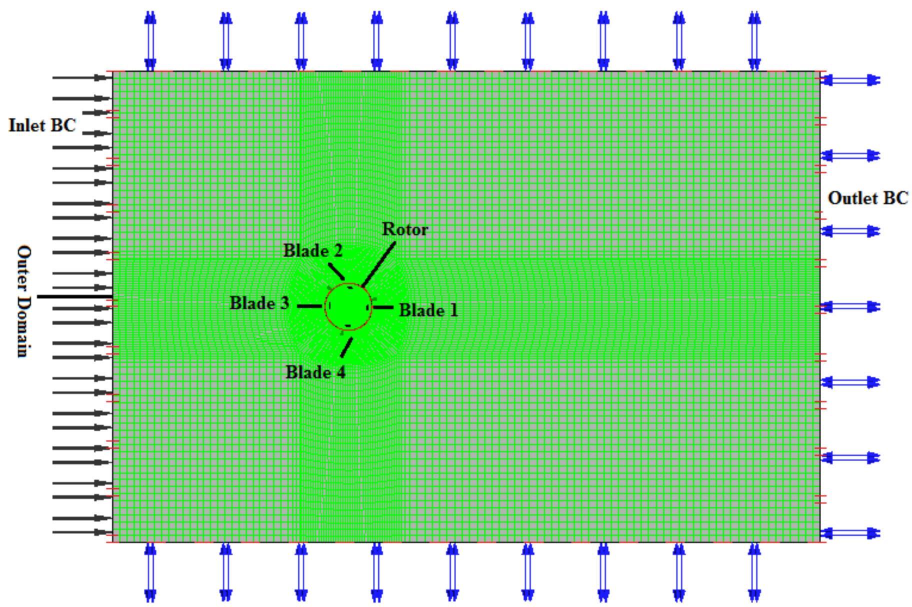

Fig. 7: Fixed pitch simulation model

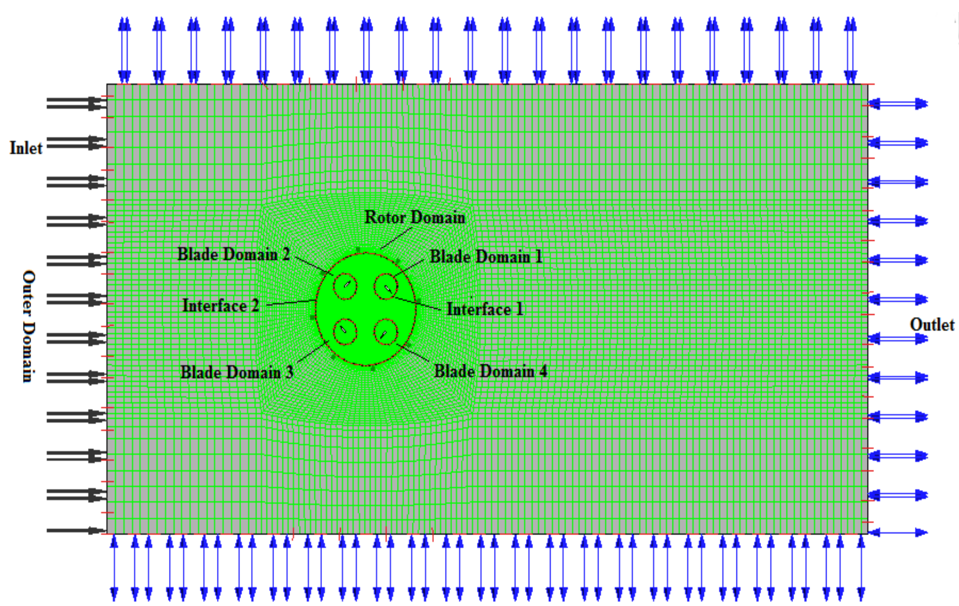

Fig. 8: Variable pitch simulation model

blade as shown in the Fig. 7. CFX expression language (CEL) is used to get the desired forces, C_p, moments and torque, etc. To control the pitch of variable turbine a length code in expression language is used. The transient simulation is run for the time duration options of 'Maximum Number of Time-steps' with maximum time-steps of 1200 sec. The solver control with an advection scheme of high resolution is used for transient solution with option of 2nd order Backward Euler Scheme. Because the 2nd order backward scheme is an implicit time stepping scheme. It is applicable for the constant and variable time-step sizes. Tight Convergence criterion with RMS Residual level of 1e-5 is applied, also the simulation is run with 1e-4, but there is no difference in the results. More detail on the RMS residual level is available in ANSYS guideline help. Meshing and modeling of variable pitch is also done in ICEM CFD. In this case we have 3 mesh regions i.e., outer stationary domain, rotating domain and blade domain. Two interface boundaries are required one for the blade domain with rotor domain and the second rotor domain with outer domain. The variable pitch simulation model is shown in Fig. 8.

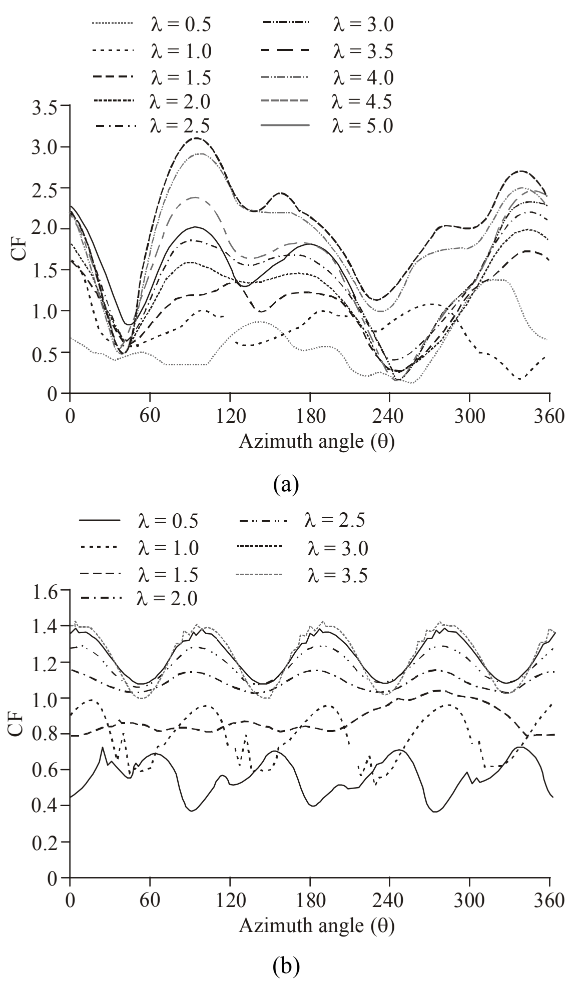

Fig. 9: Combined force coefficient for four blades vs. azimuth angle (θ), (a) fixed pitch, (b) variable pitch

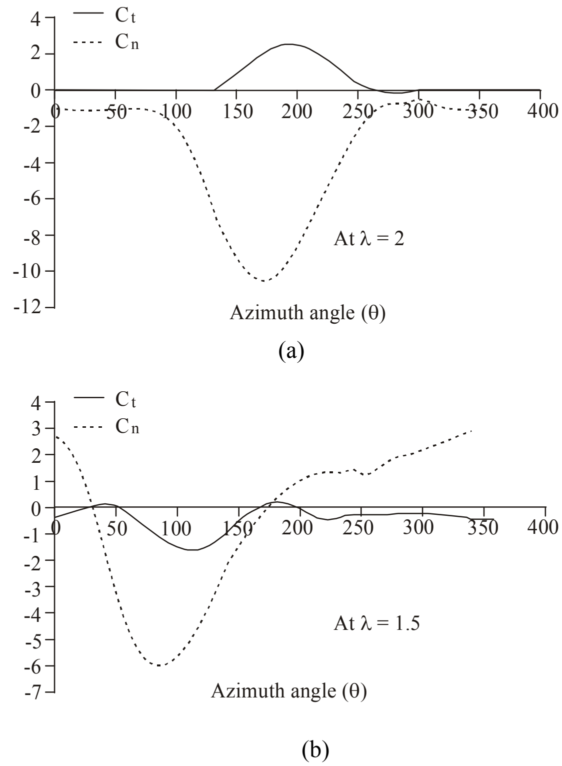

Fig. 10: Tangential & normal force coefficient vs. azimuth angle, (a) fixed pitch, (b) variable pitch

Combined or net force acting on four blades (F) is calculated with respect to blade position angle (Azimuth angle θ) for Fixed Pitch and variable pitch turbine. A coefficient is defined for this i.e., $C_F = F/0.5 \rho V^2 A$ where, V is the free stream velocity and A is the area of turbine rotor. Clearly there is a fluctuation in forces with azimuth angle at all tip-speed ratios but more peak in the case of fixed pitch. The difference in the force fluctuation for fixed pitch and variable pitch is quite evident, as shown in Fig. 9. Blade tangential forces (f_t) and Normal Forces (FN) are also calculated and a coefficient is defined for them, i.e., $C_t = f_t/0.5 \rho V^2 CH$ and C_{an}, respectively, as shown in Fig. 10. Furthermore, C_P is calculated at various tip speed ratios and we get maximum value of 46.6% at λ = 1.5 for variable pitch and for fixed pitch maximum C_P = 43.5% is observed at λ = 2 as shown in Fig. 11. Moreover, Maximum power of 196.6 KW at 33.5 rpm and 222.2 KW at 25.1 rpm against a tip speed ratio of 2 and 1.5 is observed for fixed pitch and variable pitch, respectively, as shown in Fig. 12. These all calculations are done at a velocity of 3.5 m/sec.

Experimental validation with edinburgh design Ltd: The numerical simulation results are validated both for fixed and variable pitch VATT. The CFX simulation results are compared with Edinburgh design Ltd. The

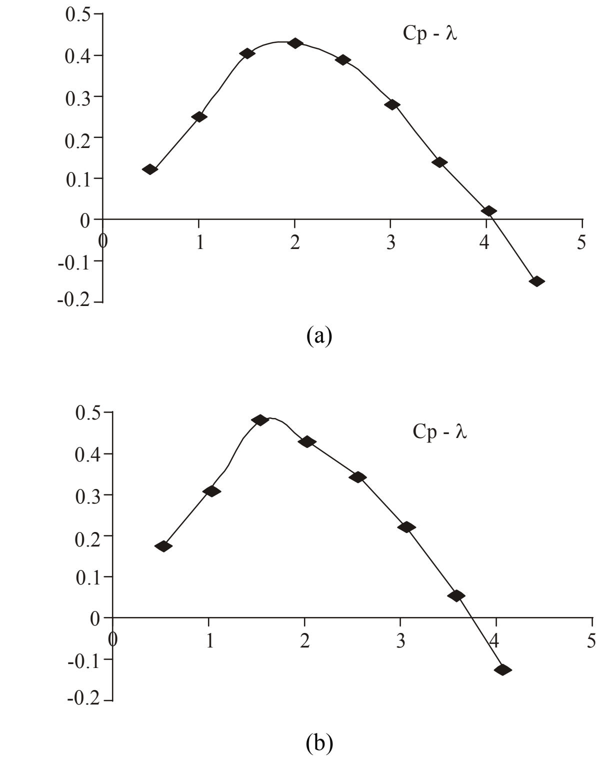

Fig. 11: Coeff. of performance vs. tip speed ratio, (a) fixed pitch, (b) variable pitch

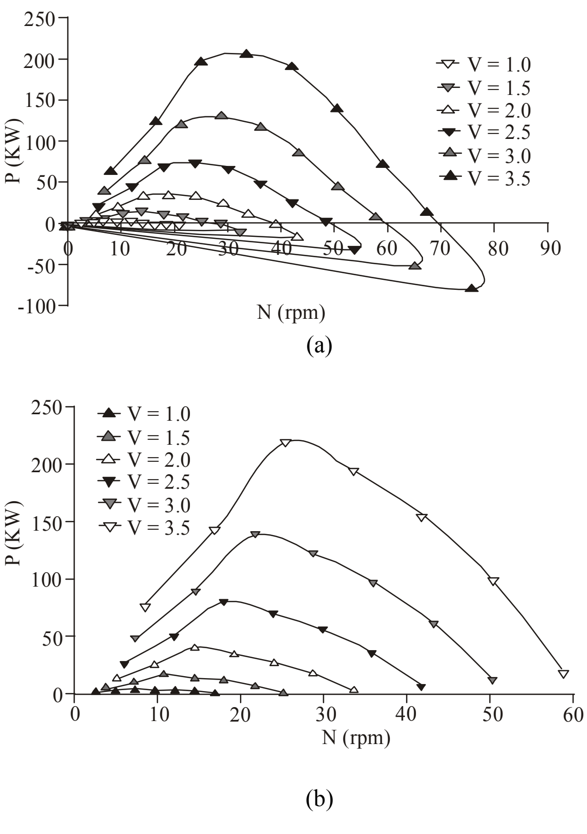

Fig. 12: Power vs. rotation, (a) fixed pitch, (b) variable pitch

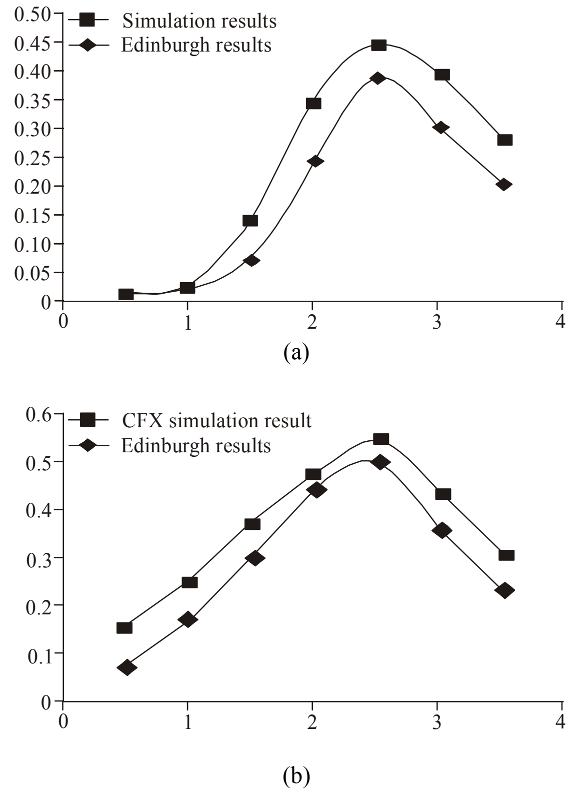

Fig. 13: Coeff. of performance vs. tip speed ratio, (a) fixed pitch, (b) variable pitch

main parameters of this model are: number of blades N = 3, chord length C = 0.375 m, diameter D = 5 m, height of blade H = 4 m and stream speed = 2.2 m/sec and blade profile is NACA0018. For more detail see (Edinburgh Design Ltd., 2006). A simulation is modeled using same boundary condition as for the actual model described above using these parameters for C_p. Edinburgh analytical results show maximum C_p of 0.382, while the numerical simulation results predict 0.44. Similarly, for the variable pitch Edinburgh analytical results calculate 0.491 and CFX results compute 0.53 as shown in Fig. 13. Although, the CFX simulation results are higher than the Edinburgh analytical results due to certain reasons: a 2-D numerical simulation is performed, also the shaft and connecting arms are not considered and dynamic stall is ignored. There is an error of 5.8 and 4.5% for fixed pitch and variable pitch VATT, respectively. After all, we achieve the level of satisfaction that the simulation method and the boundary conditions considered are realistic.

DISCUSSION AND CONCLUSION

A comprehensive CFD study is carried out for fixed and variable pitch VATT in ANSYS CFX and numbers of hydrodynamic parameters are studied. From study, we observe that the parameters considered for turbine design are practical and feasible for turbine development. Variable pitch is a good choice because of high starting torque as compared to fixed pitch. Because the major drawback of fixed pitch is self-starting under load conditions, also at start the blades are stalled most of the time and not produce enough starting torque to rotate the turbine. Moreover, the dynamic effect of forces on the blades is also high results in larger peak in tangential and normal forces, as a consequence more cyclic effects and more vibration, which can cause to unbalance and fatigue problems. Due to all these factors, the performance and power also drops and turbine life decreases. To avoid these failures, variable pitch is better option; we choose passive control mechanism to make it simple in design as possible. No doubt variable pitch design is complex as compared to fixed pitch. Although active pitch can achieve any pitch angle but make the design intricate for a tidal regime. So we can conclude that for the given parameter's passive control variable pitch tidal turbine is a better choice due to high performance, high starting torque and stable design as compared to fixed pitch.

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