



“APISAT2014”, 2014 Asia-Pacific International Symposium on Aerospace Technology,
APISAT2014

Unsteady Flow Numerical Simulation of Vertical Axis Wind Turbine

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Abstract

This paper sets up model of the flow field for vertical axis wind turbine based on airfoil DU93-W-210. FLUENT is used to solve the two dimensional unsteady incompressible N-S equations with RNG κ - ϵ turbulence model. COUPLE algorithm and sliding mesh is used to simulate the 2-D unsteady flow field of the wind turbine. The rotor power coefficient of wind energy and the variation of the wind turbine's total torque are analyzed under the variation of varied blade installation angle and chord length. As the result shows, the power coefficient of wind energy at the best installation angle is increased by 2%, and the power coefficient of wind energy in the best solidity is increased by 15%.

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Peer-review under responsibility of Chinese Society of Aeronautics and Astronautics (CSAA)

Keywords: VAWT; numerical simulation; installation angle; solidity; power coefficient of wind energy

1. Introduction

The horizontal axis wind turbine (HAWT) and the vertical axis wind turbine (VAWT) are two primary types of wind turbine. Horizontal axis wind turbines are highly developed and used in most large scale wind farms. The HAWT has to constantly yaw into the local wind direction to reach a higher power generation efficiency so it must be equipped with yaw installations. And higher requirements to the topography and wind conditions for HAWT is necessary which VAWT in a lower requirements. The manufacturing cost for VAWT could be lower than that for an equivalent HAWT due to no yaw installation is needed and straight constant section blades which also has a long service life compared to the complex three dimensional blade shape in HAWTs make it draw much attention in recent years[1,2].

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Aerodynamic problem of wind turbine rotor is the core problem of wind turbine engineering. The test of VAWT performance is the main problems of the aerodynamics of it. Considerable improvements in the understanding of VAWT can be achieved through the use of model method, CFD (Computational Fluid Dynamics) and wind tunnel experimental measurements. The wind tunnel test requires high cost, long cycle and is weaker in wind field simulation; Model method has advantages in computational speed, but is easy to diverge and results in large computational errors when in the high and low tip-speed ratio[3,4]. With the development of computer, numerical simulation technology based on CFD (Computational Fluid Dynamics) numerical simulation technology is developing rapidly. The accuracy and visibility of the simulation is also more suitable for wind turbines simulation[5]. The computational method of VAWT flow field was researched and compared by Wang Xing et al[6]. H.H. Wu analyzed the Simulation about the aerodynamic characteristics of small VAWT blade[7]. 3D numerical study and wind tunnel experiment was compared to VAWT blade roughness by Robert Howell et al[8]. But influence of chord length and installation Angle to the aerodynamic performance is not considered in all these study. Thus, it is not conducive to accurate result of the aerodynamic performances of the wind turbines.

The aim of the study is to improve the power coefficient by investigating the effect of installation angle and solidity on the performance of a four-bladed VAWT for 8 different solidities by carrying the chord lengths and 6 different installation angles. The present study set up 2D model of the unsteady flow for a fixed pitch straight bladed VAWT with sliding mesh using CFD software: FLUENT[9,10]. Much previous research on VAWTs show that even thicker airfoil produce better performance at certain scales and Reynolds numbers, so the present study focuses on the analysis of DU93-W-210 airfoil profiled blades[11].

Nomenclature

c	airfoil/blade chord, m
C_p	power coefficient
D	rotor diameter, m
R	rotor radius, m
Re	Reynolds number
U	Unperturbed velocity, m/s
θ	azimuth angle, °
λ	tip speed ratio(TSR)
σ	solidity

2. Model setup

Compared with the 3D simulation, the 2D simulation was only the aerodynamic performance of the blade airfoil shape; support arms, torque shaft and bearing disc were not considered. However, solving unsteady flow over 3D model would take much longer CPU time (several weeks per simulation). So 2D simulation can get a similar result and minimize the CPU time[12].

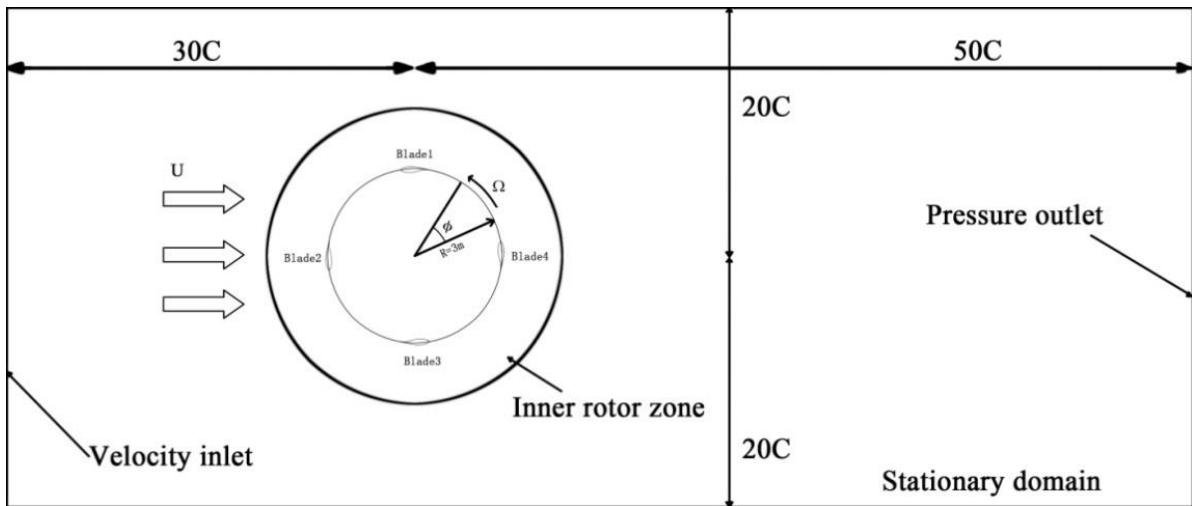


Fig. 1. Overview of the Geometry.

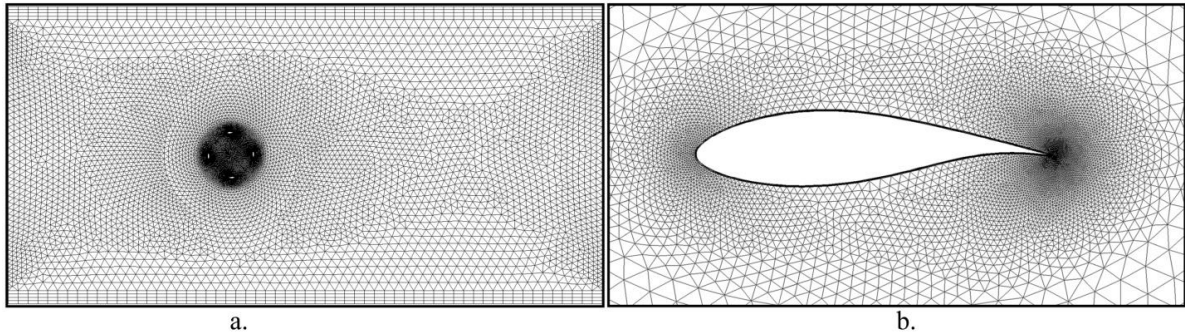


Fig. 2. (a) Overview of the mesh; (b) mesh around airfoil.

The investigation was designed around a 2D computational domain. The four- straight bladed model was created to simulate flow through the VAWT's cross section. The rotor is represented by a 1m chord DU93-W-210 airfoils and the diameter of the rotor is 6m. The computational domain contained a small inner rotor zone embedded with a 80c long (the inlet and outlet boundary conditions are placed respectively 30c and 50c upwind and downwind of the rotor) and 40c wide rectangular outer stationary domain, in order to obtain a full wake development. The stationary domain dimensions were determined by several simulations performed with successive increases in stationary domain size to ensure that the boundaries are far enough away from the turbine that has no effect on torque coefficient and overall turbine performance.

The computation was conducted on FLUENT while the mesh generation was carried out using GAMBIT. There is a sliding mesh interface at the boundary between the two sub-domains. Unstructured grid are used in both 2 sub-domains which having achieved mesh independence and the boundary layer around the blades has a first cell height Y^+ values of less than 10 with 10 layers and a growth rate of 1.2. The entire domain contained approximately 77,000 cells in which the rotor zone contained 67,000 cells. Mesh sensitivity to changes in node number was performed by successively refining the airfoil surface node density until there were no significant changes in the torque coefficient from the flow solutions.

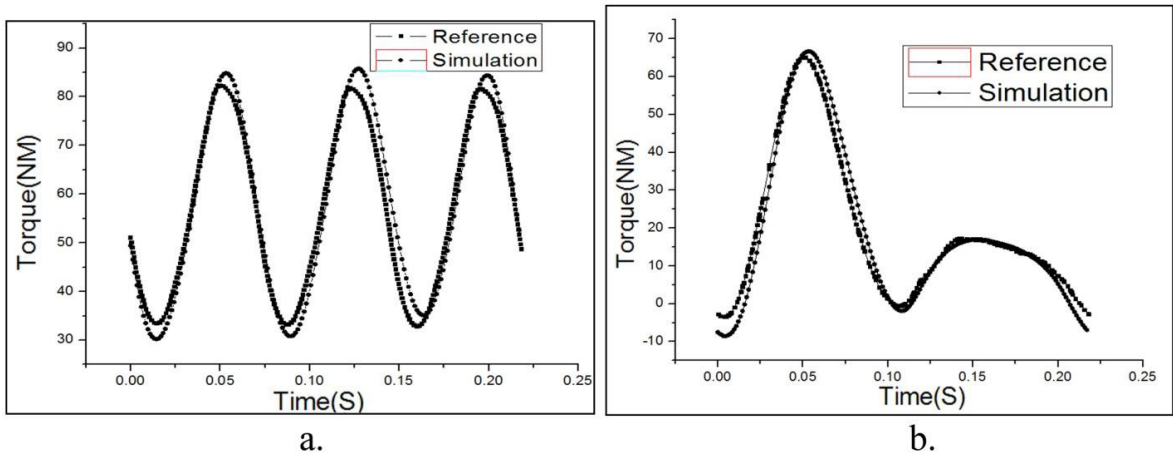


Fig. 3. Comparison of Method with Reference (a) Total Torque Ripple; (b) Single Blade Torque Ripple.

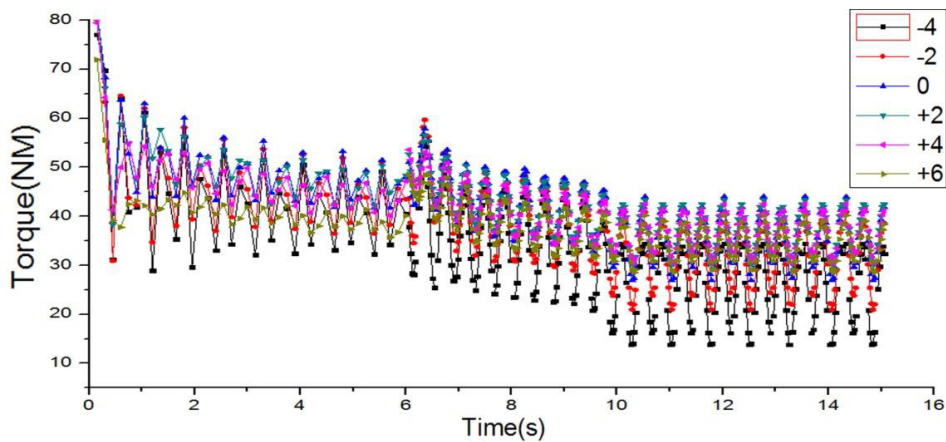


Fig. 4. Periodical Torque Results over 10 Cycles.

The left side of the domain was defined as Velocity Inlet, which allowed the magnitude of inlet flow and turbulent quantities to be specified with a flow of constant inlet velocity of 8.0m/s. The turbulent intensity of 1% and length scale of 0.01m were applied. The right side of the domain was defined as pressure outlet which relative pressure was 0pa. The other two sides of the domain (top and bottom) were defined as pressure far field which relative pressure was 0pa. The blade boundaries were defined as No Slip Walls. Both interface boundaries of the rotor zone and the stationary domain were defined as Interface designed for sliding mesh application.

The flow field was incompressible so a fully unsteady pressure-based coupled solver was selected. The two-equations RNG $k-\epsilon$ turbulence model was used which turned out to be relatively accurate results in the previous research done by Hamada et al[13,14]. The time step size was set to an equivalent of 0.02 cycle of turbine rotation and the time step convergence criteria were set to residual drop below 1×10^{-4} . The method was satisfied that negligible changes in torque occurred using a result done by Hamada which show in Fig.3.

At the start of simulation, the periodic flow field took some time to be established. Several revolutions had to be simulated before converged periodical solution was obtained. First order upwind discretisation was used during the starting-up process that was about 5 cycles. Once the solution became near periodic, second order upwind

discretisation was employed. The simulations were allowed to run for ten full rotations within which periodic convergence was observed after 7 rotations (the working condition was 40rpm so 1.5s per rotations), Fig. 4.

3. Results

3.1. Velocity distribution

An example of velocity field development of a turbine wake operating in a unsteady flow at a tip-speed ratio $=1.8$ is shown in Fig.5 for the flow time is 11.90; 12.05; 12.2; 12.35; 12.50; 12.65s which the rotor azimuth angle is 0° ; 36° ; 72° ; 108° ; 144° ; 180° . Across the turbine, the flow is seen to decelerate and a vertical wake is formed. As each blade traversing from a downwind to an upwind location, negative vorticity is shed. Likewise on the upstream-to-downstream pass, free vortex of the opposite sign is generated. The effect of regions of opposite signed vorticity contained in the shear layers at both sides of the wake is to decelerate the flow passing through the turbine while slightly accelerating the flow passing on either side. These velocity changes are clearly visible in Fig.5.

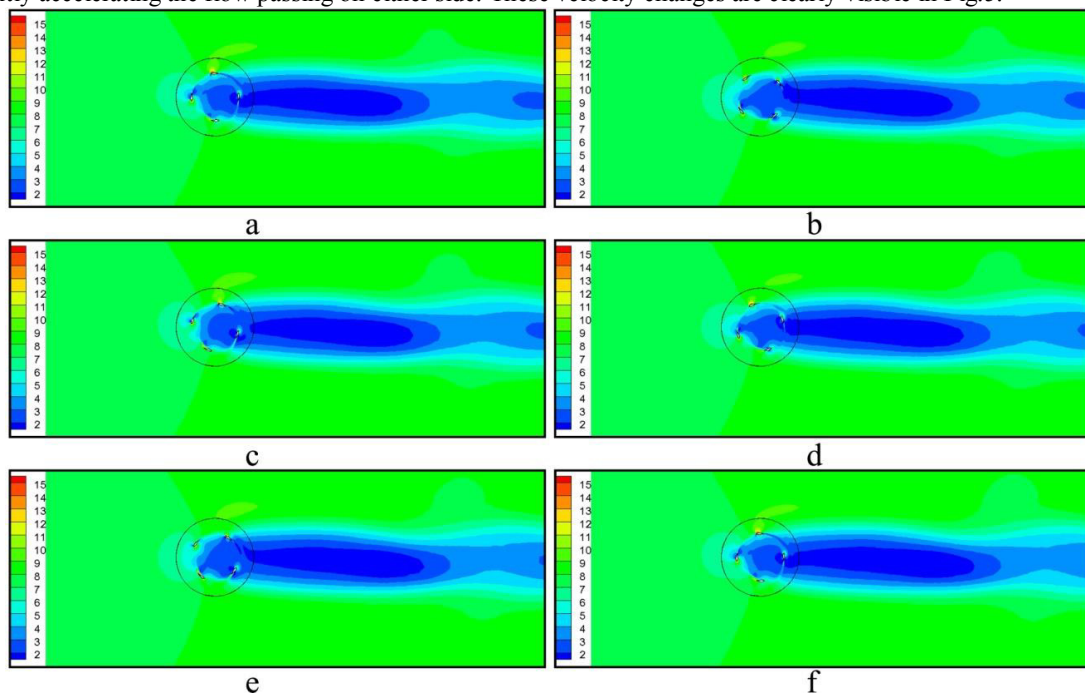


Fig. 5. Contour of Velocity Magnitude (a) $\theta=0^\circ$; (b) $\theta=36^\circ$; (c) $\theta=72^\circ$; (d) $\theta=108^\circ$; (e) $\theta=144^\circ$; (f) $\theta=180^\circ$.

3.2. Installation angle

The power coefficient changes with the variation of installation angle was showed in fig.6a Two peak power coefficient appear in different TSR when the rotor blade is in an negative installation angle. The best power coefficient of the rotor is decline as the negative installation angle increases which is decreasing at the same time. The best rotor power coefficient first rise, then declines as the positive installation angle increases while the effective operating range decline constantly. For DU93-W-210 airfoil, the result shows that the rotor best power coefficient at the best installation angle (2°) increases by 2% which turns out to be 0° , while the average of such coefficients are almost the same which has the best reasonable utilization.

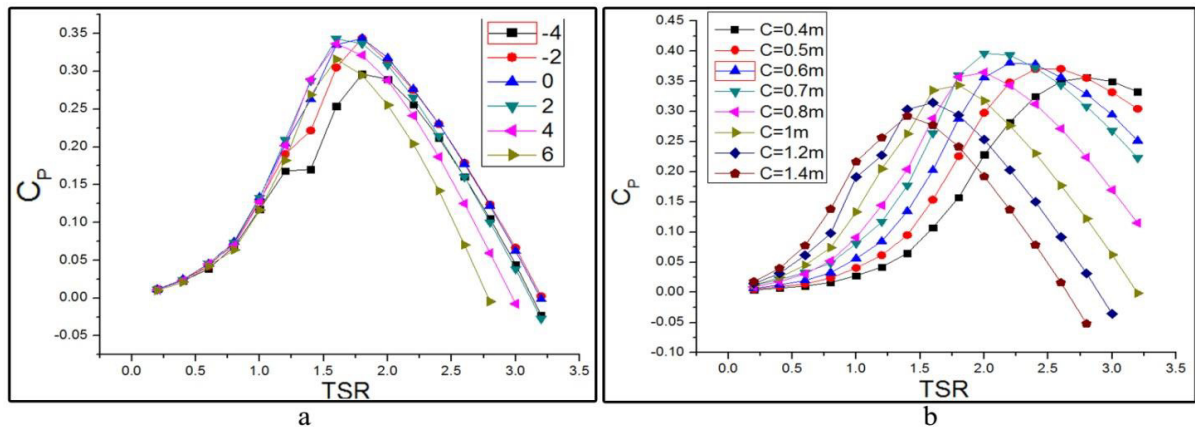


Fig. 6. Comparison of C_p (a) Different Installation Angle; (b) Different chord length.

3.3. Solidity effects

The solidity is an important factor which affects the performance of vertical axis wind turbine. The power coefficient changes with the variation of solidity are showed in this section. The test focuses on chord length while the diameter of rotor and the number of blades not being changed. As showed in fig.6b, the power coefficient line keep move to left while the chord length is increases which means the operating range keep declining. The best power coefficient increase at first and then keep declining when the chord length is 0.7m. The power coefficient increases when the length of the chord increases while the Reynolds number is also increases. When the distribution of blades and the effect beside the vortex and wake flow of the blade become fierce, wind energy dissipates into heat energy, the power coefficient declines at the same time. For DU93-W-210 airfoil 4 blades rotor which diameter is 6m, the best solidity is the chord length at 0.7m which increases by 15% then the initial solidity and its best coefficient is at the best TSR (2.5-2.8) of the VAWT.

4. Conclusion

The influences of installation angle and solidity of the performance of the VAWT have been presented. The result shows that unsteady simulation under the RNG κ - ϵ turbulence model with sliding mesh is suitable for simulating the aerodynamic of the wind turbine. Wind turbine has a strong unsteady characteristic under working condition, the unsteady flow of the starting torque need to be considered in the early steps.

The rotor power coefficient first increases then declines as the positive installation angle increases, and decline as the negative installation angle increase. The result shows that the rotor power coefficient at the best installation angle (2°) increases by 2% then that is 0° , while the average of such coefficients are almost the same.

The rotor power coefficient first increases then decline as the chord length increase, the operating range keeps declining. Such coefficient in the best solidity increases by 15% then the initial solidity within the operating range is also increase.

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