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The Effect of Pitch Angle on the Performance of a Vertical-Axis Wind Turbine

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Abstract. Wind energy is a highly promising resource to approach a sustainable built environment. Vertical axis wind turbines (VAWT) offer the advantage of omni-directional operation over horizontal axis wind turbines (HAWT). This makes them ideal for utilization in urban environments which are characterized by frequently varying wind direction. However, a comparatively small amount of research on VAWTs has resulted in low power coefficients ($C_P$) compared to HAWT. The pitch angle ($\beta$) is a parameter which is commonly used in HAWTs to enhance their performance and is a potential optimization parameter for VAWT as well. However, a recent study based on inviscid modelling states that it will not have any significant effect on $C_P$. Therefore, in order to elucidate this claim using a viscous calculation, performance optimization of VAWTs by varying $\beta$ is investigated in the current paper. $C_P$, moment and thrust coefficient ($C_m$ and $C_T$) and angle of attack are obtained from a CFD simulation of a straight-bladed H-type VAWT using 2D Detached Eddy Simulations (DES). The turbine is operating at a tip speed ratio (TSR) of 4 and $\beta$-values of 0°, +3°, and -3° are investigated. The results show that unlike the inviscid results, increasing $\beta$ from 0° to +3° would increase $C_P$ by 4% while decreasing it to -3° will result in a 16% reduction in $C_P$.

1. INTRODUCTION

Wind energy is a highly promising alternative to fossil fuels which offers great potential for a sustainable planet in terms of availability, renewability and land use. There has been a significant global growth of installed wind power in the last decade. In the quest for a sustainable built environment there is also a growing interest in wind energy harvesting in urban environments. Due to frequently-changing wind directions in urban environments, VAWTs have received interest as a result of their omni-directional capabilities. They also offer some additional advantages over their horizontal counterparts, namely no need for a yaw and pitch system; simple blade geometries (no twist or taper); low manufacturing and maintenance costs due to having a direct-driven generator installed at ground level; and low noise level due to low tip speed ratios (TSR).

After early research on VAWT in the 1970s-1980s they suffered from a lack of interest until the mid-2000s. The research gap in the intervening period has contributed to low CP values in comparison with HAWTs. Additionally, the flow around a VAWT is very complex due to phenomena such as dynamic stall, flow curvature effects, blade-vortex and vortex-vortex interactions, viscous effects, 3D wake characteristics, and azimuthal variations of vortex shedding. This complexity has demanded a great amount of research in order to optimize VAWT performance. Recent modeling and experimental research have contributed to our understandings of these complexities. A recent inviscid study using a moderate-fidelity vorticity-transport model stated that introducing a fixed pitch angle ($\beta$) to the blade only shifts the instantaneous loads between the upwind and downwind halves of the turbine and does not have any significant effect on the CP and CT of the turbine as they are averaged values over one
revolution. As this conclusion can be generalized to the introduction of any constant circulation on the blade it is very important to verify this effect using high-fidelity viscous methods and/or experiments. Therefore, a viscous CFD simulation using 2D Detached-eddy simulation is performed and instantaneous loads, angle of attack, CP, CT and Cm values are calculated for three different pitch angles (0°, +3° and -3°) in order to further study the inviscid finding. The result of this study can help the optimization of VAWTs.

2. VAWT GEOMETRY, MESH AND COMPUTATIONAL SETTINGS

A straight-bladed H-type vertical axis wind turbine is simulated. The turbine has three blades with the symmetric NACA0015 airfoil shape and a chord-to-radius ratio (c/R) of 0.115. The diameter (D) of the turbine is 1 m and it is operated at a moderate tip speed ratio (\( \lambda \)) of 4 where tip speed ratio is defined as the ratio between the turbine rotational speed (\( R_\Omega \)) to the freestream velocity (\( U_\infty \)) (see Equation 1). The freestream velocity is 7 m/s which is a reasonable mean value for a VAWT. The approach-flow and incident-flow turbulence intensities are 5% and 3.96% respectively and the turbine rotational speed (\( \omega \)) is 56 rad/s.

\[
\lambda = \frac{R_\Omega}{U_\infty} \quad \ldots \ldots \ (1)
\]

A schematic of the VAWT illustrating the directions of rotation and wind, azimuth (\( \theta \)) and an illustration of the circle for the calculation of experienced velocity is shown in Figure 1. Another schematic depicting VAWT blade cross-section showing the flow angle (\( \phi \)), angle of attack (\( \alpha \)), pitch angle (\( \beta \)) and the freestream, induced and experienced velocity vectors is shown in Figure 2. The arrow for pitch angle in Figure 2 shows the positive direction, corresponding to the blade leading edge pitched inwards towards the center of rotation of the turbine.

The fluid domain for the simulation is divided into a rotating core of two times the diameter (D) of the turbine, and a non-rotating part (20D length \times 10D width) surrounding the rotating core where the distance from the inlet and outlet of the domain to the center of rotation is 5D and 15D respectively.

A hybrid mesh consisting of triangular cells in the rotating core and quadrilateral cells elsewhere is generated which consists of 673,471 cells (see Figure 3). The mesh has an average orthogonal quality, skewness and aspect ratio of 0.96, 0.1 and 1.6 and a minimum orthogonal quality of 0.23. A smooth interface between the rotating and non-rotating domains is provided in terms of cell size and stretching ratio, and the near wall cell edges are made normal to the wall.

A mesh sensitivity analysis was done by performing calculations using URANS with the transition SST turbulence model on a coarser mesh (289,397 cells) and a finer one (921,185 cells) to investigate whether the mesh is sufficiently fine. The analysis showed that the key parameter in the simulation, Cm, shows a negligible change when the mesh is further refined from the medium to the finer mesh. The grid convergence index (GCI) was utilized in order to quantify the error and the GCIfine and GClcoarse for the medium-fine mesh pair were found to be 0.75×10^{-2} and 1.02×10^{-2}, respectively. Safety factor (Fs) of 1.25 was used in the calculation of GCI. Therefore, the medium mesh was deemed to be sufficiently fine and the rest of the calculations were performed on this mesh.
The CFD simulation was performed using the commercial CFD software package ANSYS Fluent 16.1 based on the finite volume method (FVM). The method discretises the computational domain into finite volumes and solves the governing equations of fluids for continuity and momentum. The SIMPLE pressure-velocity coupling and 2nd order discretization schemes were utilized. The side walls were represented as symmetry boundary conditions along with a constant velocity inlet, a zero-pressure outlet and no-slip condition for the airfoil walls. A sliding mesh interface was defined between the rotating core and the non-rotating domain. The solution was initialized using a steady-state solution of the RANS equations using the realizable k-ε turbulence model with enhanced wall treatment. The simulation was performed for 30 revolutions of the turbine. No data were sampled during the first 5 revolutions in order to assure elimination of the transient effects. Over the remaining 25 revolutions which were used for data sampling the change in CP between successive revolutions was well below 1%. A time step of $1.56 \times 10^{-3}$ s was employed which corresponds to an angular rotation of 0.5° per time.
step; CFL number between 5-20 in the airfoil region. 20 iterations per time step were employed in order to obtain scaled residuals on the order of $10^{-5}$.

Turbulence was modeled using the Detached-Eddy Simulation (DES) hybrid RANS-LES model. In this approach an LES model is used for the main region of the flow where large turbulent structures are dominant while for the sub-grid turbulent scales in the near-wall region a URANS approach is employed. Both the Delayed DES (DDES) shielding function and curvature correction were employed in the LES domain. In the RANS domain the transition SST model was selected as this model couples the $k-\omega$ SST transport equations with two other equations, i.e. an equation for prediction of the transition onset based on the momentum-thickness Reynolds number and a second equation for intermittency and can give a better prediction of the transition onset in the boundary layer. Therefore, this can result in more accurate results for VAWT flow types where the flow behavior is dependent on the development of the boundary layer on the airfoils.

Fig 3. Medium mesh for the VAWT simulation.

The geometrical angle of attack ($\alpha_{geo}$) is usually used for VAWTs in order to provide a first estimate for variation of angle of attack. As the name implies the geometrical angle of attack is defined based on geometrical relations while assuming zero induced velocity ($u_{ind}$); see Equation 2. This means it assumed that the blade experiences the freestream velocity in x-direction and the operation of the turbine has no effect on slowing down the flow. This is not physical as the turbine exerts a thrust force opposite to the direction of the flow which extracts energy from the flow and slows it down (the kinetic energy is transferred from the flow to the turbine; see Figure 2). This means that for a correct determination of the angle of attack the induced velocity is required, after which the experienced x-velocity ($u_{x,exp}$) can be obtained.

$$\alpha_{geo} = \tan^{-1}\left(\frac{\cos \beta}{\sin \theta + \lambda}\right) \ldots \ldots (2)$$

Due to the presence of a local stagnation area near the airfoil it is very challenging to determine the experienced x-velocity and experienced angle of attack. It therefore needs to be
sampled at a finite distance from the airfoil. The current study approximated the experienced x-
velocity on a circle with the same radius as the turbine but with the center shifted 0.2D upwind.
This way, a constant distance is kept from the blade for the sampling during the whole
revolution. The experienced angle of attack ($\alpha_{\text{exp}}$) is calculated based on a vector summation of $u_x$, $\alpha_{\text{exp}}$ and the blade rotational velocity vector $R\omega$ at each value of $\theta$.

3. RESULTS AND DISCUSSION

The variation of geometrical and experienced angle of attack versus azimuth is shown in Figure 4. As anticipated, it is observed that due to the presence of induced velocity the experienced angle of attack is smaller than the geometrical value. As the flow loses energy after passing through the upwind half of the turbine, a much lower experienced x-velocity is found when approaching the downwind half (see Figure 5). The difference between geometric and experienced angle of attack is therefore largest in the downwind region. The effect of the pitch angle on the experienced angle of attack is an almost constant shift of the same magnitude throughout the whole revolution.

![Fig 4. Angle of attack for the three fixed-pitch cases, $\lambda = 4$.](image1)

![Fig 5. Non-dimensional experienced x-velocity for the three fixed-pitch cases, $\lambda = 4$.](image2)

When the pitch angle is increased from 0° to +3°, a higher x-velocity in the windward half of the rotation is experienced while this value is lower in the leeward half (see Figure 5). The opposite effect was observed for a decrease in pitch angle. This is in contrary to the finding from the inviscid results which predicted an insignificant effect on induced velocity as a result of adding a constant finite and small circulation to the blade during each revolution. The discrepancy can be a result the presence of the boundary layer due to viscous effects and
subsequent effects on the vortex shedding and the wake. Small ripples around $\theta = 20^\circ$, $220^\circ$ and $330^\circ$ (Figure 5) are a local result of passing blades on experienced x-velocity.

Fig 6. Force in the flow direction versus azimuth for three fixed pitch angles, $\lambda = 4$.

Fig 7. Moment coefficient versus azimuth for three fixed pitch angles, $\lambda = 4$.

In terms of non-dimensional force in flow direction (Figure 6) and moment coefficient (Figure 7), an opposite behaviour to the experienced x-velocity was observed for both the upwind half and the downwind-leeward quartile. This is due to the fact that a lower experienced velocity means higher induced velocity and higher force in the flow direction, and consequently a higher moment coefficient.

Introduction of the pitch angle resulted in a shift of non-dimensional force in flow direction and moment coefficient between the upwind and downwind halves of the turbine. This was also stated in the inviscid results. However, the integral of the moment coefficient over the time times the tip speed ratio, which makes the CP, is significantly affected by varying the pitch angle (see Table 1). Increasing the pitch angle from 0° to +3° will increase the CP by 6% while decreasing it from 0° to -3° will drop the CP by 27% which is a very notable influence. This is in contrast to the result reported by Simão Ferreira et al. A negligible effect on CT was predicted by the current study (Table 1) as well as the inviscid study.

Table 1. Non-dimensional power and thrust coefficient for different fixed-pitch cases, $\lambda$

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$C_p / C_{p,0}$</th>
<th>$C_T / C_{T,0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3°</td>
<td>0.73</td>
<td>0.98</td>
</tr>
<tr>
<td>+3°</td>
<td>1.06</td>
<td>1.01</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

In this study the effect of pitch angle on the power coefficient (CP) of a VAWT was investigated using 2D hybrid URANS-LES viscous simulations using the DES approach combined with the transition SST turbulence model. The following conclusions can be drawn:

In qualitative agreement with previously reported inviscid simulation results, the instantaneous loads and moment were shifted between upwind and downwind regions as a result of varying the pitch angle.

In contrast to the inviscid results, introducing a pitch angle to the blade resulted in a significant change in CP.

Although increasing the pitch angle results in higher CP the reduction in CP is much stronger when the pitch angle is decreased.

The difference between the current study and the inviscid results can be a result of development of the boundary layer due to presence of viscosity, and consequent influences on the induced velocity and wake.

A future 2.5D simulation and investigations at different tip speed ratios are planned to further study these effects.

5. ACKNOWLEDGEMENTS

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