Flow divergence around higher-solidity straight-bladed vertical axis wind turbines

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Abstract
As the aspect ratio of a vertical axis wind turbine decreases, the peak power coefficients reduce. Here, detailed URANS CFD results are used to examine these losses and how they affect flow diveregence. Changes in the 3D flow divergence around the turbines were seen to also significantly effect the power production and tip losses of the turbine.
Keywords: *vertical axis wind turbine, computational fluid dynamics,*

Introduction

Vertical axis wind turbines (VAWTs) experience complex aerodynamics due to the continuously varying angle of attack of the blades as they rotate, and the two passes of the blades through the oncoming wind. The low rotational speeds (expressed as blade speed ratios $\lambda=U_{blade}/U_{wind}$) of higher-solidity turbines results in high effective angles of attack and rapid pitch changes and dynamic stall on the blades. Unsteady 2D cross-slice simulations of rotating medium to high solidity turbines include these effects, and often show vortices being shed by the blades in their upwind pass, which then interact with the blades on the downwind pass, but are unable to accurately model experimental results, usually showing higher maximum power coefficients that occur at higher blade speed ratios. The absence of blade tips, with their expected lower efficiency was usually blamed for this discrepancy. CFD and experimental measurements [e.g. 1,2,3] have confirmed the importance of these tip vortices on the overall turbine flow field.

McLaren *et al.* [4] considered the lack of the third (vertical) direction restricting the flow divergence around the turbine to the cross-plane to be an important part of the discrepancy, and incorporated a velocity correction factor to account for the vertical divergence of the approaching wind speed. This velocity correction reducing the 2D approach speed was based on the square root of the ratio of drag coefficients for a perforated circular cylinder (40% open area) with an infinite aspect ratio to that with an aspect ratio (1.2) of their experiments. This correction provided a good match of the maximum power coefficient and its corresponding blade speed ratio. However, the flow divergence around a turbine is expected to be far more complex than this approximation technique supposes.

Here the three dimensional flow divergence around a VAWT, and its effect on turbine power production, is explored in detail.

Methodology

The 3D flow around a rotating straight-bladed H-type VAWT was modeled using an unsteady RANS CFD code. The turbine geometry used was similar to previous experimental and numerical work done by the current group [4]; three 0.4m chord NACA 0015 profile (with slightly rounded trailing edge) straight blades, with a turbine diameter of 3m (so the solidity is 0.43). Turbine heights of 1.5m, 3m, 6m, 12m and 24m were used, corresponding to turbine aspect ratios ($AR_{turbine}$ = blade length/diameter) ranging from 0.5 to 8. A small rotating domain 7.5m in diameter contains the turbine blades (and their highly resolved grids) within a much larger (25x25x50m) stationary domain. Tests were performed to ensure that the solutions were independent of the grid and time step resolutions and overall domain size.

The inlet flow was fixed at 12 m/s with a turbulence intensity of 1%. The URANS equations were solved with the Menter's [5] SST k-ε/k-ω hybrid turbulence model as was used in [4]. Symmetry was used at the turbine mid-height to halve the required computational domain and grid. Three to five different turbine rotational speeds for each geometry, allowed the peak power to be clearly identified.

Results

The peak power coefficients ranged from 0.35 for $AR_{turbine}$=8 down to 0.295 for $AR_{turbine}$=0.5, all occurring at a blade speed ratio $\lambda_{pkpower}$ of about 1.8. There is a very small trend toward a lower $\lambda_{pkpower}$ with decreasing turbine aspect ratio. The corresponding peak power coefficient in the 2D case (i.e. infinite turbine aspect ratio) is about 0.37.

Flow divergence in front of the turbine was examined with a number of different measures. Considering the amount of flow passing through a projection of the turbine's frontal area (as a fraction of the farfield oncoming flow) allows a bulk evaluation of the amount of flow divergence and where it occurs. The upstream flow divergence is larger and occurs farther upstream as the turbine aspect ratio increases (Figure 1).

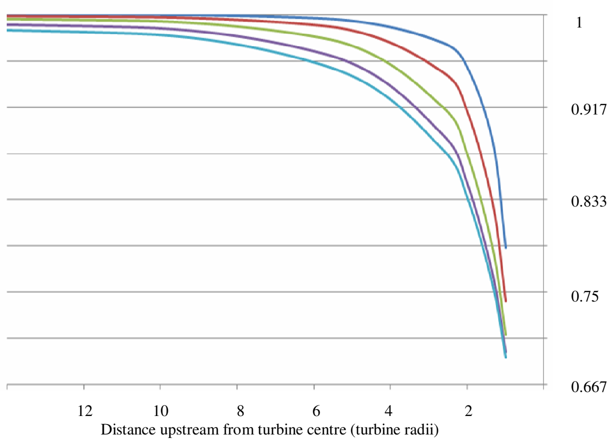

Figure 1 Average velocity in projected area upstream of the turbine (as fraction of farfield velocity). Turbine aspect ratios from top: 0.5, 1, 2, 4,8.

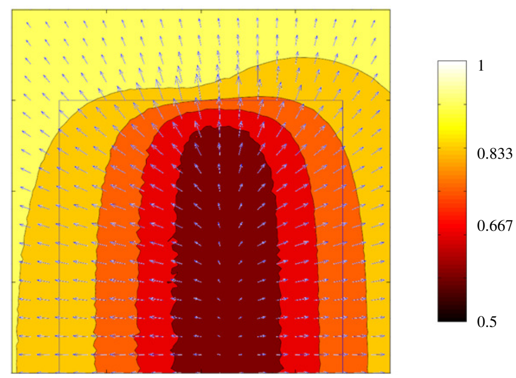

Figure 2 Average velocities on a cross-plane immediately upstream of the AR=2 turbine (at 1.05 radii turbine upstream of the turbine centre) as a fraction of farfield velocity. Dotted box shows the turbine projected area.

The flow divergence immediately upstream of the turbine was also examined in detail both on the crossplanes (as seen in figure 2) and through the curved blade path itself. For the $AR_{turbine}$=4 and 8 turbines, the results are very similar, with 58% of the oncoming flow actually going through the blade pass, while as the aspect ratio decreases, the fraction increases to 60, 62 and 67% for the $AR_{turbine}$=2,1,0.5 cases respectively. This is surprising as it means higher wind velocities are actually entering the turbine, even though the shorter turbines are producing less power (about 16% less for $AR_{turbine}$=8 to 0.5). However, this is reasonable - the lower power turbine presents less of a resistance to the wind, so diverts less flow. The divergence values are also suggestive of a single pass turbine, which agrees with the very low powers/torques seen on the second downwind pass of the rotating blades.

The blade torque curves were also examined at varying distances from the blade tips. As has been seen previously [6], there is a significant reduction in torque near the tips associated with the formation of tip vortices. Here, with the shorter (lower $AR_{turbine}$) turbines, the increased fraction of the blades near the tips results in the overall reduction in peak power coefficient. However, this power reduction is decreased by the increase in flow actually passing through the turbine.

Conclusions

Detailed examination of the flow divergence around VAWTs with various $AR_{turbine}$ was performed. Power decreases with aspect ratio are not just a function of tip losses, but also how upstream flow divergence occurs.

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