Characterisation of the Unsteady Flow in the Nacelle Region of a Modern Wind Turbine

Frederik Zahle and Niels N. Sørensen
Wind Energy Division, Risø National Laboratory for Sustainable Energy, DTU, DK-4000 Roskilde, Denmark
frza@risoe.dtu.dk

Abstract

A 3D Navier-Stokes solver has been used to investigate the flow in the nacelle region of a wind turbine where anemometers are typically placed to measure the flow speed and the turbine yaw angle. A 500 kW turbine was modelled with rotor and nacelle geometry in order to capture the complex separated flow in the blade root region of the rotor. A number of steady state and unsteady simulations were carried out for wind speeds ranging from 6 m/s to 16 m/s as well as two yaw and tilt angles. The flow in the nacelle region was found to be highly unsteady, dominated by unsteady vortex shedding from the cylindrical part of the blades which interacted with the root vortices from each blade, generating high tangential velocities in the nacelle region. For pure axial inflow the averaged nacelle wind speed varied approximately linearly with the free stream wind speed, whereas the nacelle flow angle changed significantly with wind speed. The nacelle anemometry showed significant dependence on both yaw and tilt angles with yaw errors of up to 10° when operating in a tilted inflow.

1 Introduction

On modern wind turbines nacelle anemometry measurements are used primarily in the yaw control of the turbine, for startup and shutdown, but can also be used to establish the power curve of the turbine. The industry standard for measuring the flow speed and yaw angle is to place a sonic anemometer at the rear of the nacelle which measures the horizontal velocity components. It is, however, well-known that there is considerable uncertainty associated with this measurement technique. One factor of uncertainty is due to the highly unsteady flow in the near wake of the rotating blades. Another factor is that a measurement in hub height might not be representative of the average flow speed and yaw angle across the entire rotor disc. The variation in inflow could be caused by the upstream terrain, wakes from neighbouring turbines, atmospheric turbulence and velocity shear. Another issue is that standard practice is to establish the relationship between the freestream wind speed (FSWS) and the nacelle wind speed (NWS) as well as the freestream flow angle (FSFA) and the nacelle flow angle (NFA) based on one reference turbine, which is subsequently used on other turbines regardless of local conditions such as terrain and park effects.

An analysis by Dahlberg et al. [1] based on experimental data from a number of wind farms identified critical issues in relation to power curve measurements using the nacelle wind speed. The tilt angle of the flow over the nacelle was identified as one issue that was critical to correct measurement. Masson and Smaılı [4] used CFD to investigate the detailed flow over the nacelle establishing relationships between the FSWS and the NSW. In this work an actuator disc was used in place of the actual blade geometry.

The mechanical power of a wind turbine is approximately proportional to $\cos^2(\psi)$, where $\psi$ is the yaw angle [3]. This means that a yaw error of 10° results in a reduction of 3% in the power production. Over the life span of a wind turbine this amounts to a significant loss in production, as well as increases in fatigue loads on the turbine due to the cyclic variation in the loading. These simple considerations suggest that correct measurement of the yaw angle should be of very high priority in the design of the turbine, and it could even be argued that with the continuous increase in size of wind turbines, alternative methods for measuring the yaw angle should be investigated to overcome the difficulties outlined above.

The aim of this paper is to investigate the flow properties in the nacelle region of a turbine for a number of wind speeds to assess whether characteristic flow patterns can be identified, which could lead to improvements to the guidelines for placement of the nacelle anemometer or the corrections applied to the measured flow quantities. The turbine that was used in this work is the 40 m diameter Nordtank NKT 500/41 stall regulated turbine, which is equipped with LM 19.1 blades, and has a nominal power output of 500 kW. Although this turbine is not pitch regulated, it is believed that it is still representative of a modern
turbine, and can provide useful insight into the basic flow mechanisms that govern in the nacelle region of a turbine. The present turbine was also chosen because a recent measurement campaign has been carried out on this turbine by Diznabi [2]. This paper will, however, focus solely on the numerical results.

2 Computational Setup

2.1 Flow Solver

For all computations the EllipSys3D pressure based incompressible Reynolds averaged Navier-Stokes flow solver written by Michelsen [6] and Sørensen [14] is used. The code uses the finite volume method, solving for the primitive variables $u, v, w$, and $p$, in general curvilinear coordinates. The variables are stored in a colocated grid arrangement, and odd/even pressure decoupling is avoided using the Rhie-Chow interpolation [5]. The iterative SIMPLE or PISO algorithm is used to advance the solution in time using a second-order accurate scheme. The convective terms are discretised using either the second order upwind difference scheme, SUDS, or the Quadratic Upstream Interpolation for Convective Kinematics Scheme, QUICK, and the viscous terms are discretised using central differencing. The momentum equations are solved decoupled from each other using a red/black Gauss-Seidel point solver. To accelerate the convergence of the pressure-correction equation a multigrid solution strategy is implemented combined with the additive Schwarz method, where each subdomain is solved for simultaneously. To further accelerate the convergence of the solution, grid and time step sequencing is used.

The code is fully parallelised using the MPI library with a multiblock decomposition of the solution domain. The block-block communication is done through one layer of ghost cells around each block. The cell vertices are required to coincide on interfaces such that conservation can be maintained.

For computations of flow over aerofoils and wind turbine blades the EllipSys3D code uses the $k-\omega$ SST model by Menter [17], because of its good performance in wall bounded adverse pressure gradient flows.

2.2 Computational Mesh

The stall regulated Nordtank 500 turbine is equipped with LM 19.1 blades, and has a cylindrical nacelle with a diameter of 2.0 m and a total length of 8.9 m including the spinner. The computational model of the turbine has been simplified compared to the actual geometry. The model contains the three blades, spinner and nacelle, however, the tower has been omitted since this simplifies the meshing considerably. To simplify the computational effort further, the nacelle was not stationary but rotated along with the spinner and rotor. Furthermore, the rotor was completely rigid. All simulations were carried out with uniform inflow, therefore no ground boundary was included in the simulations.

The computational surface mesh was generated using Gridgen and contained a total of 108 blocks of $32 \times 32$ cells. The blades were resolved with 256 cells in the chordwise direction and 96 cells in the spanwise direction, with a $64 \times 64$ tip cap. The nacelle was resolved with 24 blocks of $32 \times 32$. The volume mesh was generated using the hyperbolic mesh generator HypGrid [11] and grown out to form a sphere with a diameter of approximately 280 m corresponding to 7 rotor diameters with 128 cells in the normal direction. The first cell height in the boundary layer was set to $1 \times 10^{-6}$ to ensure $y^+$ values of less than 2. The mesh thus contained a total of 432 blocks of $32 \times 32 \times 32$, totalling 14.2 million cells. Figures 1 and 2 show sideviews of the mesh as well as the detailed surface mesh on the nacelle.

In Figure 2 the position of the nacelle anemometer is indicated by a red sphere. The exact coordinates of the anemometer position is $x=0$ m, $y=2.1$ m, $z=7.17$ m.

3 Computational Parameters

A total of nine simulations were carried out in this study: Six steady state moving mesh simulations with an inflow velocity ranging from 6 m/s to 16 m/s in steps of 2 m/s. In these simulations the turbine had zero yaw and tilt. Three unsteady moving mesh simulation were carried out at 8 m/s at 0°, 5°, and 10° yaw. Since the domain is axi-symmetric, these simulations were also used to investigate the effect of tilt.

The computations were all carried out using the QUICK scheme to discretise the convective terms while the SIMPLE algorithms was used to solve the coupled velocity/pressure equations for the steady state and unsteady simulations. All simulations were carried out assuming fully turbulent flow using the The $k-\omega$ SST model. The Nordtank turbine rotates at a speed of 27.1 RPM or 2.8379 rad/s. To obtain a reasonable temporal resolution, the time step in the unsteady simulations was set to $\Delta t = 2.01275 \times 10^{-3}$ at the finest grid level corresponding to 1100 time steps per revolution or 0.328° per time step. At the two coarser grid levels the time steps were succes-
sively increased by a factor of two yielding a time step of $\Delta t = 8.051018 \times 10^{-3}$ at grid level 3. Table I summarises the computational parameters.

The simulations were carried out on the Risø DTU cluster *Thyra* which contains 128 nodes of two dual core 2.2Ghz AMD CPU’s connected by means of an Infiniband network. On 14 nodes a steady state simulation is fully converged in approximately 4 hours using three levels of grid sequencing. The unsteady simulations were run on 27 nodes with three layers of grid and time step sequencing. On the finest grid and time step level one revolution was computed in
Table 1: Summary of the computational parameters for the simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Time integration</td>
<td>SIMPLE</td>
</tr>
<tr>
<td>Convective terms</td>
<td>QUICK</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>$k-\omega$ SST</td>
</tr>
<tr>
<td>Time step</td>
<td>$2.012755 \times 10^{-3}$ seconds</td>
</tr>
<tr>
<td>Subiterations</td>
<td>4</td>
</tr>
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...approximately 2.4 hours.

4 Results

Figure 3 shows the mechanical power as a function of wind speed for the steady state computations. As can be seen there is good agreement at the lower wind speeds, whereas EllipSys3D overestimates the power at higher wind speeds. This trend has also been observed in other simulations on stall regulated turbines, and can mainly be attributed to the fact that RANS solvers generally have difficulty predicting the stall on thick aerofoils correctly. Figures 4 and 5 show the tangential and normal force distributions on the blade for the six wind speeds. Table 4 summarises the mechanical power and thrust force of the turbine.

Three unsteady computations were also carried out at a wind speed of 8 m/s. One with axial flow corresponding to the steady state computations and two at 5° and 10° yaw, respectively. Table 4 summarises the results of these simulations on the three grid levels. As can be seen the unsteady simulations predict a slightly higher mechanical power than the steady state computations. The solution was found to be sufficiently mesh independent since the mechanical power varied with approximately 1% between grid level 2 and 1. The results also show that the yawed inflow conditions result in a reduction in power production proportional to $\cos^{1.7}(\psi)$ and a reduction in thrust proportional to $\cos^{0.8}(\psi)$, which is in good agreement with the findings in Madsen and Sørensen [3].

Turning to the analysis of the flow characteristics in the nacelle region, firstly, the steady state computations will be analysed. These simulations were all carried out with zero yaw and tilt angles. Since the...
Table 2: Mechanical power and thrust force for the steady state computations.

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<tr>
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<tbody>
<tr>
<td>6</td>
<td>65.2</td>
<td>24.80</td>
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<tr>
<td>8</td>
<td>182.3</td>
<td>37.80</td>
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<tr>
<td>10</td>
<td>330.4</td>
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<td>480.0</td>
<td>57.50</td>
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<tr>
<td>14</td>
<td>610.5</td>
<td>63.30</td>
</tr>
<tr>
<td>16</td>
<td>720.0</td>
<td>67.80</td>
</tr>
</tbody>
</table>

Table 3: Mechanical power and thrust force for the unsteady computations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Mech. Power [kW]</th>
<th>Thrust [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3</td>
<td>L2</td>
<td>L1</td>
</tr>
<tr>
<td>0yaw-s</td>
<td>-</td>
<td>182.3</td>
</tr>
<tr>
<td>0yaw-u</td>
<td>88.3</td>
<td>186.0</td>
</tr>
<tr>
<td>5yaw-u</td>
<td>86.8</td>
<td>185.0</td>
</tr>
<tr>
<td>10yaw-u</td>
<td>82.5</td>
<td>182.0</td>
</tr>
</tbody>
</table>

solution is steady state there is no true time variation in the solution. To obtain azimuthally varying flow quantities, the Cartesian velocity components were transformed to a polar coordinate system, and based on the tangential velocity, $V_\phi$, and the axial velocity, $W$, the nacelle wind speed (NWS) and the nacelle flow angle (NFA) were computed as a function of the azimuthal angle $\phi$:

$$ V_\phi = -U \sin(\phi) + V \cos(\phi) $$

$$ \text{NWS}_\phi = \sqrt{V_\phi^2 + W^2} $$

$$ \text{NFA}_\phi = \arctan(V_\phi/W) $$

Following a right handed coordinate system, $V_\phi$ is, when viewed from downstream, defined positive for a clockwise rotation around the $z$-axis, which is oriented in the axial direction. NFA is defined positive for an anti-clockwise rotation around the $y$-axis, when viewed from above. To obtain an azimuthal average of the NWS and NFA, these quantities were integrated along a circle with a radius corresponding to the vertical position of the probe locations.

$$ \text{NWS} = \int_0^{2\pi} \text{NWS}_\phi d\phi \bigg|_{r=\text{const}, z=\text{const}} $$

$$ \text{NFA} = \int_0^{2\pi} \text{NFA}_\phi d\phi \bigg|_{r=\text{const}, z=\text{const}} $$

where $r$ is equal to the $y$ position of the probe and $z$ is equal to the $z$ position of the probe. The NWS and NFA extracted from the unsteady simulations were simply constructed substituting the time averaged $U$ and $W$ velocities in the expressions in Equations 2 and 3.

Figures 6 to 8 show contour plots of the $z$-vorticity, the nacelle flow angle, and the tangential velocity in an $x$-$y$ plane at $z=7.17$ m, corresponding to the nacelle probe position for the 8 m/s steady state simulation. Each blade appears to generate three counter-rotating vortices that induce high tangential velocities, thus locally increasing the tangential flow angles. The large negative flow angles are generated at the interfaces between the outermost vortices of negative vorticity and the neighbouring vortices of positive vorticity. The strongest inner vortex of positive vorticity generates the positive flow angles close to the nacelle surface. Notice also that the flow angle as expected is positive in the region where the blade generates a positive torque due to the wake rotation which is opposite to the blade rotation.

Figure 9 shows the azimuthally averaged NWS versus the FSWS for the steady state simulations at the nacelle anemometer position. The extracted velocity is quite close to the FSWS at the lower wind speeds, but exceeds the FSWS slightly at higher freestream wind speeds. This result suggests that, although present, the variation of axial induction with wind speed has limited influence in the nacelle region where the blades are cylindrical and non-lifting.

In relation to positioning of nacelle anemometers, it is relevant to investigate the sensitivity of the NWS and the NFA to the vertical position of the nacelle anemometer. Figure 10 shows the normalized NWS
Figure 6: Contour plot of the z-vorticity at z=7.17 m.

Figure 7: Contour plot of the NFA at z=7.17 m.

Figure 8: Contour plot of the NWS at z=7.17 m.

as a function of vertical distance at z=7.17 m, corresponding to the plane where the nacelle probe is positioned for the six wind speeds. The NWS varies significantly with vertical distance as much as 15% from y=1.5 m to y=2.5 m, where the velocity gradient is strongest. Figure 6 suggested that the normalized NWS did not vary significantly with wind speed. However, Figure 8 clearly shows that this is not the case. It so happens that at a height of y=2.1 m, where the nacelle anemometer is located, the normalized NWS is quite close to 1 for all wind speeds. However, as is also evident, the NWS varies significantly at other vertical positions, with as much as 8% at y=2.5 m.

Figure 8 shows the NFA as a function of vertical distance. As for the NWS the flow angle is also highly sensitive to the vertical position with a variation of as much as 12° from z=1.5 m to z=2.5 m. A perhaps more critical finding is that at the nacelle probe position the flow angle varies between -6.5° and 0° for the six wind speeds, which complicates the use of corrections of the measured flow angle on operating turbines.

Steady state simulations provide fast and reliable results for flows that are physically steady state. However, for inherently unsteady flows, a steady state solution does not necessarily provide an average solution equivalent to the average of an unsteady solution. A steady state solution converges towards one solution that is steady, which depends on the exact initial conditions and numerical settings. As such it was necessary also to carry out an unsteady simulation to validate to what extent the steady state solutions were representative of the mean flow in the
nacelle region of the turbine.

Figures 10 and 11 show the NWS and the NFA for 10 consecutive revolutions at the nacelle probe position, as well as the azimuthally binned curve. The NWS signal is highly unsteady and the blade passages are smeared considerably but still detectable in the azimuthally binned curve. There is also large variation in the flow angle, with variations of \( \pm 15^\circ \). In the flow angle signal a 3P frequency is clearly visible. The steady state solution is also shown in the figures, which captures the 3P frequency for both the velocity and flow angle.

Turning to the variation of the NWS and the NFA as a function of vertical distance above the nacelle, Figures 12 and 13 show the averaged profiles over 10 revolutions as well as the steady state solution. Looking firstly at the NWS it can be seen that the unsteady and steady state solutions qualitatively agree quite well, predicting the minimum and maximum positions of velocity at the same heights. The steady state solution does, however, overpredict the wind speed compared to the unsteady solution by approximately 4%. This is likely due to the fact that the wake vortices in the steady state solution are stationary, whereas the unsteady solution contains higher frequency shedding of the vortices, which on average will cause a smearing of gradients in the flow. The same trend is visible for the NFA in Figure 13, where the steady state flow angle is 4° lower than that extracted in the unsteady simulation. However, the location of minimum flow angle is predicted in the same vertical position in both simulations.

The last part of the present investigation concerns the effect of tilt and yaw on the measured flow quantities on the nacelle. Looking firstly at the case of tilt, Figure 14 shows the normalized NWS for three tilt angles, 0°, 5°, and 10°. The tilt angle clearly has a strong effect on the measured flow speed, with a 10% reduction in the NWS from 0° tilt to 10° tilt at the anemometer position. The reason for the large shift in flow speed is that the root vortex which gives rise to a speed up effect is shifted upwards due to the tilt angle. Likewise, the NFA is strongly affected by tilt, giving rise to a 10° difference in the measured flow angle when the tilt is increased from 0° tilt to 10°.

When the turbine operates in yaw the NWS profile changes, however, not as drastically as for tilt. As is evident the speedup region shifts downwards with increasing yaw angle, due to the movement of the root vortices. The measured NWS at the nacelle anemometer position shifts approximately 4% when operating in yaw. The NFA is predicted quite accurately relatively to the zero yaw computation with only little error. As for the NWS, the minimum flow angle position is also shifted downwards for increasing yaw angle.

5 Conclusions

In this paper the characteristics of the flow in the nacelle region of a stall regulated turbine has been investigated. It has been shown that a distinct flow pattern exists with a complex set of vortical structures, which induce high tangential velocities in the region where nacelle anemometers are typically placed. It was found that the flow pattern persists for a number of different wind speeds, yaw and tilt angles. From
Figure 12: Nacelle wind speed (NWS) as a function of blade 1 azimuthal angle extracted at the nacelle probe.

Figure 13: Nacelle flow angle (NFA) as a function of blade 1 azimuthal angle extracted at the nacelle probe.

Figure 14: Comparison of the steady state and unsteady averaged normalized nacelle wind speed (NWS/FSWS).

Figure 15: Comparison of the steady state and unsteady averaged nacelle flow angle (NFA).
the steady state simulations it was found that the nacelle wind speed was predicted quite accurately compared to the free stream wind speed, whereas the nacelle flow angle was more sensitive. This sensitivity was shown to be related to the very high gradients in the tangential wind speed resulting in a significant variation in nacelle flow angle with height above the nacelle. When operating in tilt the flow around the nacelle influenced the nacelle wind speed and flow angle considerably. Yaw misalignment did not have as strong an influence on the measurement of wind speed and flow angle. In general these findings suggest that a detailed numerical analysis of the flow in the nacelle region of a turbine could be very useful for positioning the nacelle anemometer. Furthermore, the results indicate that it is very difficult to make simple corrections to the measured quantities that will be valid for all flow conditions, particularly off-design conditions.

**Acknowledgements**

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References


