Effect of ground clearance on power performance of a single wind turbine and a wind turbine row
Commissioned by DONG Energy Wind Power A/S

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Preface

This work is carried out by DTU Wind Energy, and commissioned by DONG Energy Wind Power A/S.

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## Nomenclature

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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>$A$</td>
<td>rotor area</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$a$</td>
<td>constant in relation of Charnock</td>
<td>[-]</td>
</tr>
<tr>
<td>$a_c$</td>
<td>induction</td>
<td>[-]</td>
</tr>
<tr>
<td>$C_\mu$</td>
<td>eddy viscosity coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$C_P$</td>
<td>power coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$\tilde{C}_P$</td>
<td>power coefficient, normalized with the true available power</td>
<td>[-]</td>
</tr>
<tr>
<td>$\hat{C}_P$</td>
<td>power coefficient, normalized with the hub height velocity at 2.5 rotor diameters upstream</td>
<td>[-]</td>
</tr>
<tr>
<td>$C_{T_p}$</td>
<td>power coefficient based on the local averaged actuator disk velocity</td>
<td>[-]</td>
</tr>
<tr>
<td>$C_T^*$</td>
<td>thrust coefficient based on the local averaged actuator disk velocity</td>
<td>[-]</td>
</tr>
<tr>
<td>$D$</td>
<td>rotor diameter</td>
<td>[m]</td>
</tr>
<tr>
<td>$F_T$</td>
<td>rotor thrust force</td>
<td>[N]</td>
</tr>
<tr>
<td>$g$</td>
<td>gravitational acceleration</td>
<td>[m s$^{-2}$]</td>
</tr>
<tr>
<td>$I_H$</td>
<td>total turbulent intensity at hub height in the freestream</td>
<td>[-]</td>
</tr>
<tr>
<td>$k \equiv \frac{1}{2}u_i^2$</td>
<td>turbulent kinetic energy</td>
<td>$[m^2 s^{-2}]$</td>
</tr>
<tr>
<td>$P$</td>
<td>rotor power</td>
<td>[kW]</td>
</tr>
<tr>
<td>$R$</td>
<td>rotor radius</td>
<td>[m]</td>
</tr>
<tr>
<td>$U_H$</td>
<td>freestream at hub height</td>
<td>[m s$^{-1}$]</td>
</tr>
<tr>
<td>$\langle U_{AD} \rangle$</td>
<td>averaged actuator disk velocity</td>
<td>[m s$^{-1}$]</td>
</tr>
<tr>
<td>$u_*$</td>
<td>friction velocity</td>
<td>[m s$^{-1}$]</td>
</tr>
<tr>
<td>$z_H$</td>
<td>hub height</td>
<td>[m]</td>
</tr>
<tr>
<td>$z_0$</td>
<td>roughness length</td>
<td>[m]</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>dissipation rate of turbulent kinetic energy</td>
<td>$[m^2 s^{-3}]$</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Von Kármán constant</td>
<td>[-]</td>
</tr>
<tr>
<td>$\nu_T$</td>
<td>turbulent eddy viscosity</td>
<td>$[m^2 s^{-1}]$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
<td>$[kg m^{-3}]$</td>
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1 Introduction

In previous work [19], we have investigated the influence of the ground clearance on the power performance of a single NREL-5MW reference wind turbine [3] using the Computational Fluid Dynamics (CFD) tool EllipSys3D [6, 12]. A parametric study of the hub height (between 70 and 140 m, with 5 m interval) showed that the power coefficient, normalized by true wind resource over the rotor area, changes by only 0.2%, with a maximum at a hub height of 95 m. The study was carried out for a fixed wind speed of 8 m/s and turbulence intensity of 5%. While the influence of the ground clearance on the power performance normalized by the true wind resource is small, the effect on the wake recovery was found to be significant. For a low hub height of 70 m, more wind tends to move over the wind turbine and deflects the wake downwards, compared to taller hub heights. The wake recovery is delayed at low hub heights, because the wake mixing from below is obstructed. In the present work, we want to quantify this effect on the power performance of a row of 5 wind turbines. In addition, the study is extended by simulating wind speeds between 5 and 11 m/s with 0.5 m/s interval and the influence of the hub height on the induction zone is investigated.

The numerical setup of the CFD simulations is discussed in Section 2. The results and conclusions are presented in Sections 3 and 4.

2 Setup

The numerical setup is based on simulations of a single wind turbine and a wind farm of van der Laan et al.[16–18]. A summary of the setup is given in the preceding sections, together with the definition of the test cases.

2.1 Test cases

Simulations of a single wind turbine and a row of 5 wind turbines with 7 rotor diameters spacing, for a row aligned wind direction are performed. In both cases, a parametric study of the freestream wind speed at hub height $U_H$ and the hub height $z_H$ is carried out:

- $U_H = 5 – 11$ m/s, with steps of 0.5 m/s.
- $z_H = 70 – 140$ m, with steps of 5 m.

The modeled wind turbine is based on the NREL 5-MW reference wind turbine [3], which has a rotor diameter and an original hub height of 126 and 90 m, respectively. The aerodynamic performance and operational data is given in Figure 1. In terms of ground clearance normalized by the rotor diameter $D$: $z_H/D - \frac{1}{2}$, a range between 0.056D and 0.61D with an interval of 0.040D is investigated.

2.2 Wind turbine modeling

The wind turbine is modeled as an Actuator Disk (AD) [7]. The AD forces are implemented as sources terms in the momentum equations. In the single wind turbine simulations, the forces are based on airfoil data [10]. The power is determined as an integral of the rotational forces taken over the AD. It is known that AD based on airfoil data often overpredicts the power and thrust by 10% and 2-3% [10, 16].

In the wind turbine row simulations, a different AD force method is employed [16] that is developed for wind farm simulations, where only information on the power and thrust coefficients are known, while airfoil data is not available. The force method is labeled as the AD variable scaling method. When a wind turbine operates in the wake another, the power and thrust coefficients are unknown because the freestream wind speed is unknown. The AD variable scaling method circumvents this problem by using a power and thrust
Figure 1: Aerodynamic characteristics of the NREL-5MW reference wind turbine.

The coefficient as function of local velocity averaged over the AD, $\langle U_{AD} \rangle$:

$$C_p = \frac{P}{0.5 \rho A \langle U_{AD} \rangle^3}, \quad C_T = \frac{F_T}{0.5 \rho A \langle U_{AD} \rangle^2},$$  

(1)

where $P$ is the power, $F_T$ is the thrust force, $\rho = 1.225$ kg/m$^3$ is the density and $A$ the rotor area. The $C_p - \langle U_{AD} \rangle$ and a $C_T - \langle U_{AD} \rangle$ curves are obtained from a parametric run of single wind turbine simulations for wind speeds between 4-25 m/s, with a 1 m/s interval, where a normalized thrust force distribution (based on a full rotor simulation of the NREL-5MW) is scaled with the known thrust coefficient $C_T$ of Figure 1. For each hub height case, new $C_p - \langle U_{AD} \rangle$ and $C_T - \langle U_{AD} \rangle$ curves are calculated. In the wind turbine row simulations, the $C_p - \langle U_{AD} \rangle$ and $C_T - \langle U_{AD} \rangle$ curves are used to determine $C_T^* \rho$ and $C_p^*$ from the local $\langle U_{AD} \rangle$. The $C_T^*$ is used to scale the normalized thrust force distribution, while $C_p^*$ is used to determine the power production. Rotational forces are neglected because their effect of the power deficit is negligible [17]. The AD variable scaling method has proven to work well for wind farm simulations [17]. In addition, it does not suffer from the overprediction in power and thrust as observed in the AD based on airfoil data because the AD variable scaling method relies on a calibration with the reference power and thrust curves.
2.3 Flow solver

The flow is solved steady state using Reynolds-averaged Navier-Stokes (RANS). RANS calculates the mean flow directly and it requires a turbulence model that can handle the complex flow around the wind turbine. The chosen turbulence model is discussed in the preceding section. The in-house finite volume code EllipSys3D is used [6, 12]. The RANS equations are solved with the SIMPLE algorithm [8] and the QUICK scheme [4] is used to discretize the convective terms. The flow variables are stored in a collocated manner. To avoid decoupling of the pressure with body forces, the pressure equation is solved with a modified Rhie-Chow algorithm [9, 11, 13].

2.4 Turbulence modeling

RANS methods model all turbulence scales. For high Reynolds number flows, i.e. a wind turbine wake, the turbulence model has a large influence on the flow solution. Therefore, the choice of turbulence model is very important for wind turbine simulations in RANS. In the present work, we use the \( k-\varepsilon-f_p \) turbulence model [18], which is developed for wind turbine wake simulations. The \( k-\varepsilon-f_p \) shows improved velocity and power deficits with respect to the standard \( k-\varepsilon \) model.

2.5 Domain

The grid and boundary conditions for the single wind turbine simulation is given in Figure 2. The boundary condition are discussed in the preceding section. The domain is box-shaped and it has a size of \( 25 \times 16 \times 16D^* \) in stream-wise, lateral and vertical direction. For convenience we define the dimensions with an alternative rotor diameter \( D_* = 125 \text{ m} \), instead of \( D = 126 \text{ m} \). A subdomain, called the wake domain, is defined in which a uniform spacing is applied in all directions. The wake domain has dimensions \( 12.5 \times 3 \times 3.5D^*_w \), and it is shown as a blue square in Figure 2. Grid studies show that a spacing of \( D/10 \) in the wake domain is enough to obtain a grid independent velocity deficit [10, 18]. However, in the present single AD simulations we choose to use a much finer spacing because:

1. The current study is looking for relatively small differences in the power performance.
2. The relative orientation of the AD and the grid cells should be constant to avoid numerical differences in the integral of the power for different hub heights. (i.e. grid spacing = hub height step size \(/n\), with \( n \) as an integer.)

In previous work [19], we have investigated an even finer spacing of \( D_*/50 \), although the result did not change much in terms of the power coefficient. The used grid with a spacing of \( D_*/25 = 5 \text{ m} \) consists of 6.3 million cells.

The grid and boundary conditions of the wind turbine row is shown in Figure 3. The domain has a size of \( 80 \times 16 \times 16D^*_w \) in stream-wise, lateral and vertical direction. The wake domain has dimensions \( 40 \times 4 \times 4.6D^*_w \). The cell spacing is chosen to be \( D_*/10 \) because the difference in power between the up and downstream wind turbines is not as small, as observed in the single wind turbine simulation. The total amount of cells is 3 million cells.

2.6 Boundary conditions

The boundary conditions of the single wind turbine and wind farm simulations are shown in Figures 2 and 3. At the inlet, a neutral logarithmic profile is set:

\[
U(z) = \frac{\nu_s}{\kappa} \ln \left( \frac{\nu}{\nu_0} \right), \quad k = \frac{\nu_s^2}{\sqrt{C\mu}}, \quad \varepsilon(z) = \frac{\nu_s^3}{\kappa^2},
\]  

(2)
Figure 2: Grid and boundary conditions of single AD simulations. Every 4th grid line is plotted. Top: top view of the grid. Bottom: side view of the grid. Blue filled box represent the AD. Spacing inside the blue rectangles is set to $D_*/25$.

Figure 3: Grid and boundary conditions of wind turbine row simulations. Every 4th grid line is plotted. Top: top view of the grid. Bottom: side view of the grid. Blue filled boxes represent ADs. Spacing inside the blue rectangles is set to $D_*/10$. 
The profiles are in equilibrium with the RANS and turbulence equations. At the bottom of the domain ($z = z_0$), a rough wall is specified where the velocity is zero, the gradient of $k$ is zero and the dissipation is specified using eq. (2). A fully developed flow is assumed at the outlet boundary. Symmetry conditions are specified at the lateral boundaries.

2.7 Setting freestream conditions

In previous work, the undisturbed turbulence intensity and the velocity at hub height are set by the friction velocity $u_*$ and the roughness length $z_0$. In the current work, the roughness length is determined from Charnock’s relation:

$$z_0 = a_c u_*^2 / g,$$

where $a_c$ is constant set to 0.016, $g$ is the gravitational acceleration set to 9.81 m/s$^2$. As a result, the undisturbed turbulence intensity at hub height cannot be set to a constant. For a given hub height $z_H$ and undisturbed velocity a hub height $U_H$, the friction velocity is determined from solving the following nonlinear relation:

$$U_H = \frac{2 u_*}{\kappa} \ln \left( \frac{z_H u_* g}{a_c} \right) \Rightarrow a u_* + b u_* \ln(u_*) + c = 0,$$

where

$$a = \frac{1}{\kappa} \ln \left( \frac{U_H g}{a_c} \right),$$

$$b = -\frac{2}{\kappa},$$

$$c = -U_H,$$

using a numerical nonlinear solver with a tolerance of $1 \times 10^{-6}$. The results of $u_*$ and $z_0$ are plotted in Figure 4. This leads to a undisturbed turbulence intensity that varies between 5.07% ($z_H = 140$ m, $U_H = 5$ m/s) and 6.13% ($z_H = 70$ m, $U_H = 11$ m/s) for the investigated range of hub heights and wind speeds, as shown in Figure 5.

![Figure 4: Friction velocity and roughness length as function of hub height and wind speed.](image-url)
3 Results and Discussion

3.1 Single wind turbine

For all single wind turbine simulations, the standard power coefficient $C_P$ is plotted as contours in Figure 6. The left plot of Figure 6 shows that $C_P$ increases with hub height because the wind resource increases due to the decreasing shear, as also observed in previous work [19]. The variation of $C_P$ with wind speed follows the trend in power performance of the reference wind turbine, see Figure 1. This trend is removed when the power coefficient is normalized with the one obtained from the simulation with $z_H = 140$ m (right plot of Figure 6). The result of Figure 6 are also plotted as lines in Figure 7.
Figure 7: Power performance as function of hub height and wind speed. Right plot is normalized by the power performance for a hub height of 140 m.

Figure 8 shows the power coefficient normalized by the true wind resource:

\[
\tilde{C}_P \equiv \frac{P}{\frac{1}{2} \rho s U^3 \int (z) dA}
\]

where the integral \( \int U^3(z) dA \) is taken over the rotor area (for an undisturbed profile). There seems to be an optimal region of \( \tilde{C}_P \) around \( z_H = 95 \) m, as also found in previous work [19].

Figure 8: Power performance based on the true wind resource as function of hub height and wind speed. Right plot is normalized by the power performance for a hub height of 140 m.

### 3.2 Wind turbine row

The power coefficients of the four downstream wind turbines, normalized by the power coefficient of the first wind turbine are plotted in Figure 9. All plots show that the power production of the downstream wind turbines increases with increasing hub height or ground clearance. This is caused by the fact that the wake recovery is faster for taller hub heights, which is clearly visible in Figures presented in Appendix A Figure
10 shows the sum of power performance of the 4 downstream wind turbines, normalized by the sum of power performance of the 4 downstream wind turbines, for a hub height of 140 m. A gain in power between 35% and 50% can be achieved when the hub height is increased from 70 m to 140 m. Figure 10 illustrates how the downstream power deficit is decreased with increasing hub heights.

We can identify two causes for the faster wake recovery for increasing hub heights:

1. For taller hub heights, the wake can mix with both the ‘undisturbed’ wind from below and above, while the bottom up mixing is obstructed for low hub heights.
2. In the assumed neutral boundary layer, the eddy-viscosity $\nu_T$ is linearly increasing with height: $\nu_T = u_* \kappa z$, which enhances mixing for increasing hub heights.

The second cause has a large influence on the wake mixing and needs to be further investigated. The eddy viscosity can also be written as a velocity scale (i.e. the friction velocity $u_*$) and a turbulent length scale $\ell_t$:

$$\nu_T = u_* \ell_t$$

(6)

In the neutral logarithmic layer, the turbulent length scale is linearly increasing with height: $\ell_t = \kappa z$. It can be questioned if the neutral logarithmic layer assumption, or a linearly increasing turbulent length scale, is still valid for the tallest investigated hub height of 140 m. It is possible to limit the turbulent length scale of the boundary layer using the global length scale limiter of Apsley and Castro [1], as also applied in previous work [14, 15] for AD simulations including Coriolis. This setup could also be applied to investigate the effect of tall hub heights on the wake recovery.
Figure 9: Power performance of downstream wind turbines normalized by the power performance of the first wind turbine.

Figure 10: Sum of power performance of downstream wind turbines normalized by the sum of power performance for a hub height of 140 m.
Figure 11: Power performance in the wind turbine row, normalized by the power performance of the first wind turbine, for all hub heights, for a wind speed of 8 m/s.
3.3 Induction

The induction at \((x,y,z) = (-2.5D,0,z_H)\), in terms of streamwise velocity normalized by the freestream, is plotted for all single and wind farm simulations in Figures 12 and 13, as contours and lines, respectively. The induction at hub height decreases slightly for taller hub heights. The irregular variation of the induction with hub height and wind speed that is observed in the wind farm simulations (right plots of Figures 12 and 13) could be a result of the calibration procedure of the AD variable scaling method as presented in Section 2.2. In this procedure, the thrust and power coefficients as function of the local AD velocity are determined by single wind turbine simulations for wind speeds between 4 m/s and 25 m/s with an interval of 1 m/s. Hence, an interpolation error can be present for the wind farm simulation for a wind speed of \(x.5\) m/s because the thrust and power coefficients as function of the local AD velocity are linearly interpolated from the calibrated values.

Figure 12: Streamwise velocity at \((x,y,z) = (-2.5D,0,z_H)\), normalized by the freestream. Left: single wind turbine, right: wind turbine row.

From analytical analysis in rotor aerodynamics [2], the induction zone can be expressed as (as also used in Medici et al. [5]):

\[
\frac{U}{U_H} = 1 - a \left[ 1 + \xi \left( 1 + \xi^2 \right)^{-\frac{1}{2}} \right], \quad \xi = \frac{2x}{D}, \quad a = \frac{1}{2} \left( 1 - \sqrt{1 - C_T} \right) \quad (7)
\]

Note that the formula is valid for negative \(x\). Figures 14 and 15 show the comparison with equation 7 and RANS results for 9 different cases, for both the single wind turbine and wind turbine row simulations. There is an overall good agreement for \(x < -0.5D\). The largest deviations are observed for the simulations with the lowest hub height (70 m). Equation 7 does not take the shear into account and this could cause the deviations for low hub heights, where the shear \(dU/dz = u_*/(\kappa z)\) is the largest.

In power curve measurements, the freestream wind speed is measured at 2.5 rotor diameters upstream of the wind turbine, which means the measured \(C_P\) is in fact calculated as:

\[
\hat{C}_P = \frac{P}{\frac{1}{2} \rho A U^3_{-2.5D}} \quad (8)
\]

\(\hat{C}_P\) is plotted in Figure 16.
3.4 Discussion of AD methods applied to shear

Two different AD force methods are applied in the RANS simulations, as presented in Section 2.2. In the single wind turbine simulations, the AD forces are based on airfoil data, and known pitch and rpm settings. The local forces at the AD interact with the shear and can result in a radial force distribution that can vary over the azimuth. Since the AD airfoil method often overpredicts power and thrust, an alternative AD force method (AD variable scaling method) is applied in the wind farm simulations. This AD methods relies on a calibration of a thrust and power coefficient as function of the local AD velocity, which assures that the correct power and thrust is set for the first wind turbine in the row. The AD variable scaling method assumes a (scalable) force distribution that is constant over the azimuth (it varies over the radius), which means that the interaction with the shear is neglected. In other words, there is an overprediction in thrust below the hub height and an underprediction in thrust above the hub height. Nevertheless, the results of single and wind turbine row simulation show similar trends in terms of induction at hub height, see Section 3.3.
Figure 14: Comparison of the induction of 9 single wind turbine simulations with equation 7.
Figure 15: Comparison of the induction of the first wind turbine in 9 wind farm row simulations with equation 7.
Figure 16: Power performance as function of hub height and wind speed taken at 2.5 rotor diameters upstream of the rotor. Right plot is normalized by the power performance for a hub height of 140 m.
4 Conclusion

The influence of the hub height and ground clearance on the power performance of a single wind turbine and a row of 5 wind turbines is investigated with Reynolds-averaged Navier-Stokes, in a neutral atmospheric surface layer. While the effect of the hub height of the power coefficient of single wind turbine, normalized by the true wind resource is negligible, the effect on the wake recovery is significant. The simulations show that the summed power performance of the 4 downstream wind turbines, normalized by the power performance of the first wind turbine in the row, increases between 35%-50% when the hub height is increased from 70 m to 140 m. For a tall hub height or a large ground clearance, the wind turbine wake is mixed with both the flow from above and below, which enhances the wake recovery compared to a small ground clearance. In addition, the assumed neutral atmospheric surface layer includes a turbulent eddy viscosity that increases linearly with height without limitation, which enhances the wake mixing for taller hub heights. It is recommended to further investigate the neutral atmospheric surface layer assumption for tall hub heights, by performing the parametric hub height study in a neutral atmospheric boundary layer where the eddy viscosity is limited.
References


A  Velocity contours

A.1  Single wind turbine
Figure 17: Stream-wise velocity contours at hub height, for a hub height wind speed of 5 m/s. AD is shown in black.
Figure 18: Stream-wise velocity contours at hub height, for a hub height wind speed of 8 m/s. AD is shown in black.
Figure 19: Stream-wise velocity contours at hub height, for a hub height wind speed of 11 m/s. AD is shown in black.
Figure 20: Stream-wise velocity contours as function of height, normalized by the inflow profile, for a hub height wind speed of 5 m/s. AD is shown in black.
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Figure 22: Stream-wise velocity contours as function of height, normalized by the inflow profile, for a hub height wind speed of 5 m/s. AD is shown in black.
A.2 Wind turbine row
Figure 23: Stream-wise velocity contours at hub height, for a hub height wind speed of 5 m/s. ADs are shown in black.
Figure 24: Stream-wise velocity contours at hub height, for a hub height wind speed of 8 m/s. ADs are shown in black.
Figure 25: Stream-wise velocity contours at hub height, for a hub height wind speed of 11 m/s. ADs are shown in black.
Figure 26: Stream-wise velocity contours as function of height, normalized by the inflow profile, for a hub height wind speed of 5 m/s. ADs are shown in black.
Figure 27: Stream-wise velocity contours as function of height, normalized by the inflow profile, for a hub height wind speed of 8 m/s. ADs are shown in black.
Figure 28: Stream-wise velocity contours as function of height, normalized by the inflow profile, for a hub height wind speed of 11 m/s. ADs are shown in black.
This work is carried out by DTU Wind Energy, and commissioned by DONG Energy Wind Power A/S.