Investigation of unfavorable winds associated with complex terrain using Detached Eddy Simulation

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ABSTRACT: Unfavorable winds are often found in complex terrain and these complicated flow phenomena such as flow separation and vortex shedding can cause difficulties in siting of wind turbines. This paper uses a DES method to depict the unsteady flows observed in the vicinity of a wind turbine location. A coastal site is selected for this study. It has been observed that the variations of wind velocities and wind directions may be large across the rotor area. The large differences in wind velocity and wind direction can cause problems to a wind turbine in operation. The CFD simulations may provide useful information to siting engineers and decision makers. As a result, wind risks associated with complex terrain may be identified to avoid unnecessary financial losses in the investment of a wind farm.

1 INTRODUCTION

Siting of wind turbines is a challenge to wind project developers and wind turbine manufacturers, especially in complex terrain. On-shore wind turbines have been increasingly placed at mountain ridges, rolling hills, plateaus and valleys. Inevitably, the complicated flow characteristics, such as vortex shedding, flow separation and re-circulation are often observed in the vicinity of turbine locations. These unfavorable winds, if not noticed, may bring negative impacts to wind farms and consequently there will be financial losses due to high maintenance costs and poor performance in energy production.

Using a two-equation RANS model, such as the standard k-ε model has been a popular practice in the wind industry (Brodeur and Masson, 2006; Jørgensen et al, 2007). The steady RANS methods resolve the mean wind velocities and the mean turbulent kinetic energy throughout the computational domain. The information provided by the RANS methods is adequate if the general flow pattern and mean flow properties are of the main interests. On the other hand, LES methods mainly focus on the calculation of turbulence spectra and modeling of detailed transient flow behaviors which may provide more information to the flow field in question. However, one drawback of LES methods is the demand of high computational costs that may prohibit a practical analysis of a wind farm.

Detached Eddy Simulation (DES) is a hybrid method between RANS and LES. DES has been successfully applied to investigate transient flow behaviors with regard to atmospheric flows over complex terrain (Bechmann et al, 2007). In general, the advantage of using DES is the alleviation of mesh requirements for both near wall regions and flow separation regions. Also, the traditional wall-function approach can be coupled with the RANS model to account for terrain roughness. Since DES uses LES only to resolve the large “detached” unsteady eddies far from walls, the DES methods can reduce the computational costs of LES whilst the transient flow behaviors are still resolved without losing significant details.
As DES methods can resolve large-scale vortex shedding and flow unsteadiness triggered by geometry, it is therefore ideal for investigation of complicated flow characteristics associated with complex terrain. This study uses a project located at a coastal site, where the unfavorable winds have caused problems to a number of wind turbines. A DES method is used to simulate the flow conditions. The main focuses are on the variations of wind velocities and wind directions across the rotor area.

2 DESCRIPTION OF THE SITE

The wind park consists of 33 wind turbines and the layout is shown as Figure 1. The rotor diameter is 80 m and the hub height is 60 m. The wind turbines are represented by the red dots and they are located in the region near the coast. The contours range from 0 m (sea level) to 152.5 m.

A turbine location “WTG16” was selected for the investigation, as the yaw-control parts of this turbine had some mechanical errors in operation. The wind directions simulated were 170° and 290° from the North.
3 METHODS

3.1 Turbulence model

This study used a SST k-ω model tailored for DES as the RANS model (Menter and Kuntz, 2002). The DES version of SST k-ω model has made a modification in the transport equation of the turbulent kinetic energy \( k \). The dissipation term \( D_k \) is modified as follows:

\[
D_k = \rho \beta^* \omega k \phi
\]

where

\[
\phi = \begin{cases} 
1 & \text{if } l_t < C_{des} \Delta \iff \text{RANS mode} \\
> 1 & \text{if } l_t > C_{des} \Delta \iff \text{LES mode}
\end{cases}
\]

\[
l_t = \frac{\sqrt{k}}{\beta^* \omega}
\]

\[
C_{des} = C_{des,k-\omega} F_1 + C_{des,k-\epsilon} (1 - F_1)
\]

The \( \beta^* \) is a model constant; \( \rho \) is the density of fluid; \( \omega \) is the specific dissipation rate; \( \Delta \) is the largest distance between the cell center under consideration and the cell centers of its neighboring cells; \( C_{des} \) is a constant determined by both the value of \( C_{des} \) calibrated for the k-ω branch and the value of \( C_{des} \) calibrated for the k-ε branch using the blending function \( F_1 \) of the SST k-ω model. Therefore, with the dynamic length scale \( l_t \), the model switches itself to RANS or LES according to the local flow properties.

3.2 Computational domain

The computational domain covers the area of 11 km \( \times \) 13 km and the domain height is 2 km above the sea level (Figure 2). The neutrally stratified atmospheric conditions were applied to the inflow boundary conditions:

\[
U(z) = \frac{u^*}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right)
\]

where \( z_0 \) is the aerodynamic roughness length; \( z \) is the height above ground; \( \kappa \) is the von kármán constant (≈ 0.4) and the \( u^* \) is the friction velocity. The boundary conditions for turbulence were assumed to be in equilibrium so that

\[
k = \frac{u^2}{\sqrt{C_\mu}}
\]

\[
\omega = \frac{\sqrt{k}}{\kappa \beta^* \lambda^\frac{1}{4}}
\]
where $C_\mu$ equals 0.03 according to the atmospheric conditions. There was no artificial perturbation applied to the inflows.

A symmetry boundary condition was applied at the top of the domain and a rough wall function was used at the bottom to account for the terrain roughness.
3.3 Mesh layout

DES is sensitive to mesh layout because the distance between cell centers is one of the criteria to determine whether RANS or LES mode is activated (1). In general, RANS mode is supposed to be activated near walls where the flows are attached. Therefore, following the suggestions made by Spalart (2001), the mesh layout has been designed to vary with height (Figure 3). A Cartesian and terrain-following mesh was used and the minimum spacing of the horizontal grids was 12.5 m. Isotropic grids were used in the regions far away from the ground.

3.4 Numerics

The DES used a hybrid differencing scheme for spatial discretization. The hybrid scheme is a combination of a second-order upwind scheme and a second-order central differencing scheme. The central differencing scheme is designed for the LES region and the upwind scheme is suitable for the RANS region.

A second-order temporal differencing scheme was applied to the transient terms of the flow equations. The CFL number was less than 1.0 in order to ensure the stability of the calculation and adequate time resolutions.

A general-purpose flow solver “STAR-CCM+” (CD-Adapco, 2009) was used for this study.

4 RESULTS

4.1 Velocity vectors

Using velocity vectors is a convenient way to depict the flow pattern. Figure 4 shows the instantaneous velocity vectors in the vicinity of WTG16 in the wind direction 170°.

Figure 4. Instantaneous velocity vectors colored by streamwise velocity in wind direction 170°.
Figure 5 shows another snapshot of the flow pattern in the wind direction of 290°. The red dots in Figures 4 - 5 denote the rotor bottom, hub height and the rotor bottom, respectively. Both Figure 4 and Figure 5 indicate the flow pattern across the rotor area is very unsteady.

Figure 5. Instantaneous velocity vectors colored by streamwise velocity in wind direction 290°.

4.2 Statistical analysis

The rapid variations of wind velocities and wind direction have significant impacts on the control of wind turbines. Frequent and large variations in wind velocities or wind directions across the rotor area can result in excessive loads on blades and yaw-control parts.

Figure 6. Time series of wind direction (Left) and probability density function of wind direction difference (Right) in wind direction 170°.

In wind direction 170°, the CFD calculated time series present different wind directions at the rotor top (100 m above ground) and the rotor bottom (20 m above ground).
The probability density function (pdf) of the wind direction difference has deviated from the design values, represented by the red curve (Figure 6).

In the wind direction 290°, not only the pdf of wind direction difference shows abnormal distribution but the pdf of wind velocity difference also shows large shift from the standard curve (Figures 7 - 8).

Figure 7 shows the wind direction at the rotor bottom has rapid and large variations and the range is between 190° and 305° but the wind direction at the rotor top is around 280° without large fluctuations. The directional difference between the rotor bottom and rotor top makes it difficult to orient the nacelle in a right wind direction and consequently the yaw-control parts may have difficulties to operate.

On the other hand, Figure 8 shows the range of wind velocity difference is between 1 m/s and 12 m/s with a mean value about 7 m/s. The large difference shows the value of “wind shear” is high. Excessive loads can occur at the blades due to the large variations of velocity difference across the rotor area. The excessive loads can also be transferred to the yaw-control parts through the nacelle. The combined effects of rapid wind direction change and large wind velocity difference can cause problems to this wind turbine.
5 CONCLUSIONS

This CFD study has performed an analysis for a specific wind turbine location using a DES method. The transient behaviors of flows across the rotor area have been simulated and the likely root causes which can account for the operational difficulties of the wind turbine have been identified. Using the DES method can provide time-dependent information to siting engineers. As a result, it enables the statistical analysis and this type of numerical simulations can depict a relatively complete picture of the turbulent flow field.

Further research will include more measurement campaigns and a link between flow field simulation and loads calculation will be established.

6 ACKNOWLEDGEMENTS

This study has been supported by Vestas Wind & Site Competence Center under the strategy of continuous improvements. The author would like to thank his colleagues - Lars C. Christensen, Line Gulstard and Frank Klintø for their time and advices.

7 REFERENCES


