Numerical Study of the Impact of Urban Terrain on the Loads and Performance of a Small Vertical Axis Wind Turbine

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Abstract. In the present study, the performance of a small vertical axis wind turbine (VAWT) is investigated in realistic urban terrain, in presence of large buildings, hill and forested area. Normally, accelerated wind can be observed on the roof-top of the high-rise buildings. Thereby, different factors such as the orography, vegetation and presence of the buildings at the site etc. influence the inflow conditions strongly and subsequently the performance and loads of wind turbines. Due to the continuously varying inflow direction, inclination and highly turbulent nature of the wind, a detailed analysis of the flow field around the building is required. A two-stages approach is preferred to reduce complexity of the problem. In the first part, the inflow conditions are investigated in the large domain by means of CFD and in the second part, performance and loads of the roof-top mounted small VAWT are investigated.

1. Introduction

As the appropriate offshore sites for large wind parks are limited in Germany, there have been efforts to find new alternatives to exploit available wind potential effectively. The transmission of electricity from offshore sites to deep inside the mainland suffers from problems such as public acceptance, electrical losses etc. Besides the expansion of onshore sites, other alternatives include sites in complex terrain, urban terrain etc. Stathopoulos et al. studied different aspect of urban aerodynamics focusing on the potential and challenges for wind energy exploitation in urban environment[1]. Mertens studied different concentrator effects of buildings and recommended that the energy yield for all concentrator configurations is limited as the wind turbine can yield energy from concentrator configuration, if they are small compared to the building[2]. The different factors such as the orography, vegetation and presence of buildings in urban terrain influence the inflow conditions for small wind turbines. Various studies have
shown that mean wind speed in urban environments is lower than the wind speed in rural areas[3, 4], but the turbulence can be stronger than in case of flat terrain due to the large shear, interaction between atmospheric boundary layer (ABL) and the present obstacles. This results into different phenomenon such as acceleration, channelling, blocking, recirculation and increasing turbulence. The “Morgenstelle Campus” of University of Tübingen near Stuttgart has been chosen for the current study. The prevailing wind direction is south-west (240°). The forest in upstream region is part of the “Schönbuch” natural park. Preliminary experimental and numerical wind resource assement of “Morgenstelle Campus” had been done by El Bahlouli[5] considering simplified geometry and RANS simulations in past.

In the present paper, the influence of orography, urban terrain and forested area on the inflow conditions for a small wind turbine is investigated by means of scale resolving Delayed Detached Eddy Simulations (DDES) in presence of the inflow turbulence. The analysis can also be the basis for the identification of a suitable locations for wind turbine installations. In future, there might be possibility to install a small wind turbine and study the performance and load characteristics of the turbine. In the subsequent section, the two-stages approach is explained. Sec. 3 gives an overview about simulation setup. In Sec. 4 the impact of orography, terrain, forest and buildings on the flow field and performance of a virtual wind turbine under such complex inflow conditions is discussed.

2. Methodology

In an independent study, two-stages simulations approach is tested and validated against theoretical solution. In the first part of the study, coarser grid resolution is used
to cover a large domain of “Morgenstelle Campus” consisting of multiple structures, vegetation present in upstream direction etc. to derive the inflow conditions for the second part of the study, in which a finely resolved simulation is performed for the wind turbine and its near flow field. The first part is simulated considering atmospheric turbulent inflow boundary conditions and wind shear profile. This stage is necessary to identify suitable locations for VAWT and the expected inflow conditions. Once the flow field is well developed in the computational domain, the transient flow field is dumped out in form of perpendicular planar interface to the flow direction at an upstream location near to the buildings. In order to mimic the real distribution of the forested area, a range of different heights and foliage densities are considered for different parts of forest. In second part of the study, the near field around a small virtual VAWT mounted on the top of high-rise building is investigated numerically. The computational domain for the VAWT simulations in the second part is smaller than domain considered in the first part.

3. Simulation setup

The simulations are carried out using the compressible flow solver FLOWer [6], which was developed by German Aerospace Center (DLR) and is continuously extended at the Institute of Aerodynamics and Gas Dynamics (IAG) of University of Stuttgart. FLOWer uses block-structured grids and it is a finite volume solver featuring a range of turbulence models. It also supports rotating structures and the CHIMERA overset grid technique to incorporate separately meshed objects by embedding them in the background grid [7]. A fifth order WENO numerical scheme has been implemented in FLOWer for better reconstruction of fluxes and more accurate propagation of vortical, turbulent structures [8]. Also, FLOWer has been extended to model the forest vegetation [9] using an approach based on Shaw and Schumann [10].

In the present study, scale resolving Delayed Detached Eddy Simulations (DDES) are performed to strike good balance between Reynolds Averaged Navier-Stokes equations (RANS) and Large Eddy Simulations (LES) [11]. The turbulent, atmospheric inflow conditions for the larger domain in stage one are realized by superimposing the
synthetically generated turbulence on a generic wind profile. The synthetic turbulence is generated by means of the Mann model [12]. The large domain is simulated considering an inflow velocity of $U_{\text{ref}} = 7.58 \text{m/s}$ at 200 m reference height with a generic log law shear profile, an atmospheric turbulence length scale $L = 50 \text{ m}$ and a turbulence intensity of $TI_0 = 10\%$. The synthetic turbulence is injected at $\approx 2L$ distance from inlet boundary. In order to reduce the impact of fluctuations during the superimposition of turbulence, the volume forces suggested by Troldborg[13] are used in a plane further downstream direction. The geometrical extent of the domain is $21L \times 20L \times 14L$ in x, y and z direction respectively.

In order to mimic the real distribution of the large forested area lying in the upstream region, a range of different heights and foliage densities are considered in respective simulation. The forested area is divided into different parts. For each part, the average height is obtained by considering many data points from the available geological data obtained from State Office of Geoinformation and Land Development. The foliage densities are approximated based on the information about distribution of tree types present in “Schönbuch” natural park. Considering winter season, the index is assumed to be in the range of 1.8-2.2. The drag force term caused due to the impact of the forest is dependent on the local foliage density $a(z)$ at different heights for the respective part. The different local foliage densities lead to different drag distributions over height. The drag term $F_w$ is defined as

$$F_w = -\rho c_d a(z)|\vec{u}| \vec{u}$$

(1)

where $c_d$ is constant drag term. $|\vec{u}|$ and $\vec{u}$ are local velocity magnitude and velocity vector respectively. The Leaf Area Index (LAI) over the height $h$ is calculated as

$$\text{LAI} = \int_z^h a(z)dz$$

(2)

The instantaneous and transient flow field is dumped out at $x=-200$ m position in the first part of the study by means of an interface as shown in fig. 1a. Based on the results from stage one, suitable building and position are selected for the stage two simulation. The inflow conditions for the stage two simulations with a virtual wind turbine mounted on the top of building, the inflow conditions are realized by a Dirichlet boundary condition based on the flow field dumped in stage one.

For the stage two simulations, a reference vertical axis wind turbine (VAWT) is selected for the current study. It is an up-scaled generic VAWT with a diameter of 7 m and a blade length of 4.2 m with symmetric NACA0021 profile having a constant chord length of 0.9275 m. The non-scaled original reference wind turbine is validated and the results are published in [14]. A fixed pitch angle of 6° is adopted and the height of the tower is 14m. The location is approximately 4.95 m from the front edge of the building B in streamwise direction and approximately in the middle of the width of the building as shown in fig. 2b. The building B is selected based on the results discussed in sub sec. 4.1. For the VAWT simulations, the background grid resolution around the selected B building is kept same as first stage. The region far away from building B is
considered in the computational domain in order to avoid the influence of boundaries and the blocking caused by the building according to the best practice guidelines [15]. The region around the wind turbine features a very fine mesh. The boundary layer around the blade is resolved with $y^+ \approx 1$. The wake region of wind turbine has a refined grid in order to resolve the wake. The wind turbine is simulated at tip speed ratio 3.

4. Results

The objective of the present study is to examine the impact of orography, forest and urban environment on the development of inflow conditions and subsequently, the performance of a small wind turbine mounted on the top of the building. The numerical set-up of the simulations of first stage (shown in fig. 1a) is described in sec. 3. The results of pure terrain simulations are discussed in sub sec. 4.1. After selecting the location of the wind turbine, the second stage DDES simulations are carried out under inflow conditions extracted from the results of the first stage. In the sub sec. 4.2 the results of wind turbine simulation mounted on the top of the building B are discussed.

4.1. Pure terrain simulations

First, in order to characterize the effect of the forested area, simulations are performed with and without forest. The resulting time-averaged boundary layer profiles of the pure terrain simulations are depicted in fig. 3 for various upstream positions in a plane $y= -4.5 \text{ m}$ passing through the highest building A. The origin $(0,0)$ is located behind the building A. At locations $x=-300 \text{ m}$ and $-200 \text{ m}$ in fig. 3, the presence of forest results into small or negative velocities near ground. This leads to an offset in the boundary layer near to the ground at all upstream locations compared to results of only terrain simulation. The velocity profiles at locations $x=-300 \text{ m}$ and $-200 \text{ m}$ without presence of forest are similar to the defined inflow velocity profile while at $x= -100 \text{ m}$
the profile is shifted vertically due to the influence of the hill. At position $x = -27$ m, the velocity at the top of the building is reduced in presence of the forest. Fig. 4 represents the normalised turbulence kinetic energy at different positions. At $x=-300$ m and $x=-200$ m it is noted that the turbulence level is increased at the upper side of the forest while at position -100 m shows high increase in turbulence level in wake region of the forest. On the top of the building, a strong influence of the forest can be seen in the turbulence level.

Figure 4: Normalised turbulence level $Y = -4.5$ m

Figure 5: Boundary layer profiles $Y=85.85$m

The resulting time-averaged boundary layer profiles of the pure terrain simulations are depicted in fig. 5 at various streamwise positions in $y$ plane ($y=85.85$ m) passing through the building B. At locations $x=-300$, 200 m and -100 m the velocity profiles without forest are not influenced strongly by the orography as compared to other plane shown fig. 3. The weak influence of orography and terrain could be attributed to relatively flat terrain with less variations in the elevation in the upstream region. The
Figure 6: Normalised turbulence level $Y=85.85$ m presence of the forest shifts the boundary layer profiles upwards. However, at the top of the building B the velocity profile with and without forest appears to be similar. The increase in turbulence level due to presence of the forest is lesser compared to fig. 4. It is noted, that at the top of the building A, the combined effect of the forest and orography on velocity profile and turbulence level is stronger than in case of building B.

![Figure 6](image)

Figure 7: Turbulence level in plane $x = -3.749$ m

In fig. 7, a lateral plane passing through building B and behind building A is shown, which depicts the normalized turbulence level. The flow field around buildings is influenced by the combined wake of the forest and orography significantly. Fig. 8 depicts the instantaneous flow field with streamlines. The flow appears to be less disturbed in the upstream region in fig. 8a on the contrary to the results with forest shown in fig. 8b. The streamlines in upstream region shown in fig. 8b depict the cross-flow through the forest in upstream region. From fig. 3, 4, 5 and 6, it is noted that over the top of the building B higher wind speed and lower turbulence level than on the top of building A are observed. Therefore, building B is selected for the further investigation for the
wind turbine simulations.

4.2. VAWT simulations

Figure 9: Moment and axial load of one blade over multiple revolutions ($\lambda = 3$)

The normalized moment and normalized axial force of a single blade over azimuth is shown in fig. 9b and fig. 9c respectively. In Fig. 9a, the relative position of the inflow over azimuth is shown. The moment and load are normalized with the maximum magnitude of the respective variables. In [14, 16], it is observed that the maximum moment occurs around $90^\circ$ azimuth position under uniform flow with very low turbulence level and from $180^\circ$ to $360^\circ$ the moment is negative with small magnitude. However contrary to findings in [14], under complex inflow conditions caused by the orography and vegetation the wind turbine behaves differently. Strong deviations can be seen in positions of peak moments in fig. 9b. The positions of peak moment differ over a wide range of azimuth angle from $60^\circ$ up to $135^\circ$. Also, a large portion of the cycle remains...
in negative moment region from azimuth position 150° to 360°. This leads to very small positive or no positive moment over the cycle. At first glance, the distribution of axial forces shown in Fig. 9c seems chaotic. However, focusing on the azimuth angle from 0° to 180°, the axial force changes within extreme range with strong gradients around 60° to 70°.

The Z vorticity around the wind turbine is shown in fig. 10a. It appears that the vortical structures of the wind turbine do not last long and are broken into small eddies. This can be attributed to the high turbulence level with large length scales. In order to understand this phenomenon, some more simulations are planned. Fig. 10b represents the $\lambda_2$ structures in the wake region of building and wind turbine. The location of the wind turbine is sufficiently away from the top in order to avoid influence from the recirculation region formed due to the building. Therefore, it is suspected that the inflow conditions dominantly influence the performance of the wind turbine.

![Figure 10: Instantaneous flow field at $\lambda = 3$](a) Z-vorticity contours  
(b) $\lambda_2$ structures

5. Conclusion and outlook

In the present study, scale resolving DDES simulations are performed to investigate the influence of orography and forest on the inflow conditions for small wind turbine mounted on the top of building. In the first part of the study, two different simulations are performed. One includes orographic features, terrain and buildings while other includes orographic features, terrain, buildings and forest in upstream region. It was observed that the presence of the forest in upstream region shifts the boundary layer in vertical direction by an offset close to the forest height. Also, it leads to smaller velocities than prescribed inflow boundary condition in the near ground region. The combined effect of orographic features like hill and forest strongly influence the flow field and turbulence level near the buildings in the wake region. It shall be noted that these findings hold for the selected orography, built environment and the forested area and inflow conditions.
In the second part of the study, based on the velocity and turbulence level from first stage results, a plausible position is selected for the investigation of wind turbine. The wind turbine was embedded in the smaller domain than the domain of first part of the study. The inflow conditions for the second part of study are realized by means of the Dirichlet boundary conditions using the transient flow-field, which is dumped out from the first part of the study. The wind turbine simulations show very different characteristics considering the moment and forces at different azimuth positions. The wind inclination, interaction between boundary layer and built environment influences the inflow conditions for the wind turbine over the top of the building and subsequently it’s performance. Future work is dedicated to understand the influence of different locations and tower height at different operating points.

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