Detached Eddy Simulations of the local Atmospheric Flow Field within a Forested Wind Energy Test Site located in Complex Terrain

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Abstract. Within a current project a wind energy test site will be installed in complex terrain in Southern Germany. On such complex orographies various inflow conditions influence the power gain and the blade loads of wind turbines. For example, forest vegetation modifies the wind direction and velocity, in addition to inclination angles caused by the complex escarpment. The scope of the present work is to characterize the influence of a forested area in complex topographies on the local flow field by means of CFD. The results will be compared to inflow conditions of wind turbines in complex terrain without consideration of forests in a wind tunnel model. Objective is to analyze the degree of influence, a forested hill introduces to the flow field on top of the terrain near the designated wind turbine position and to observe flow separation due to the vegetation. To clarify the results, simulations of flows within forests in flat terrain will be shown and compared to numerical results and measurements from literature.

1. Introduction
The investigation of wind energy in complex terrain is one of the main aspects of the Southern German Research Cluster (WindForS). Complex orographies influence the inflow conditions of wind turbines. Inclination angles, turbulence intensities and deviation of wind shear profiles depend on slope inclination of the terrain and on vegetation [1]. In flat terrains these parameters behave more homogeneous. Investigation of the local flow field in complex terrain is very important for defining the optimum position of wind turbines or wind parks. Inclination angles influence the power output of wind turbines on hills, ramps or complex orographies. Hence, Tsalicoglou [2] studied the wind turbine performance experimentally under inclined inflow conditions. Britter et al. [3] analyzed first studies of turbulent flow over a two-dimensional hill with a short roughness. A similar analysis has been investigated by Jackson and Hunt in 1975 [4]. The influence of forests in complex terrain on the local flow field has been studied by Finnigan and Belcher [5]. They investigated the flow within a forest located on a hill. Because of the speed up of the wind that results in a larger power gain in generally low speed regions, wind energy in complex terrain becomes more and more significant. Since these areas are usually covered with forests, it is important to determine the effect of forests on the local flow field and eventually on the wind turbines, normally placed on top of a complex escarpment [6]. Therefore, it is important to perform CFD simulations of the flow field to determine the flow characteristics of
the complex terrain near Stötten at the Swabian Alb in Southern Germany. Preliminary studies have already been done in previous projects [1], [7], [8]. Within the project these studies shall be extended by new simulations, which will be supported by new implementations like a new forest model. Besides, two wind turbines will be installed at this test site and the CFD simulations will later be confirmed by several measurements at the test site.

The main objective of the present study is to outline the influence of vegetation on the wind at the wind energy test site in complex terrain by means of highly resolved Detached Eddy Simulations (DES). A model of the same terrain in a wind tunnel is applied in the simulations. In the past, a lot of measurements have been done with this wind tunnel model and in the future measurements of the terrain model with consideration of forests will be studied. Therefore, it is valid to start the simulations with the new implemented forest model with the wind tunnel terrain and not with the real test site. Thus, the paper deals with the local atmospheric flow field of a complex terrain wind tunnel model with a scale of 1:400. The new implemented forest model will be considered.

2. Methodology
For CFD simulations the compressible flow solver FLOWer [9] was used, which was developed by the German Aerospace Center (DLR) and is improved continuously at the Institute of Aerodynamics and Gas Dynamics in Stuttgart (IAG). The FLOWer code uses structured meshes and was extended by a fifth order WENO scheme [10] for a better resolution, more accurate propagation and less dissipation of turbulent vortex structures.

The upcoming simulation results are performed by Detached Eddy Simulations. DES strikes a good balance between simulations of Reynolds Averaged Navier-Stokes equations (RANS) and Large Eddy Simulations (LES) [11]. FLOWer has now been extended by a new forest model implementation. Regarding this model, a forest structure can be added on the escarpment to improve previous simulations of the complex terrain. Consequently, the flow simulations will become more realistic.

Basis of the implemented forest canopy flow code is the forest model of Shaw and Schumann [12]. It’s the basis of the most forest models that can be found in literature and has often been validated. The forest model of Liu [13] e.g. is also based on this model.

In the implementation the forest structure is added as a porous medium. In the course of the implementation, a volume force is added to the momentum equation of the Navier-Stokes equations, which contains the forest drag force. This term depends on the so called local foliage density $a(z)$, which is a parameter of drag over the height for a certain part of a forest. This means that different local foliage densities lead to different drag distributions over height, resulting in special characteristic velocity profiles in the wake of forests.

The additional drag term is defined as follows:

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

This drag force is equal to the product of the local foliage density, a constant drag term (often $c_d = 0.15$ [12]) and of the local velocity. To characterize the forest density a second important parameter, the Leaf Area Index, should be considered. The Leaf Area Index (LAI) is defined as:

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

For illustration LAI = 2 characterizes a sparsely covered forest canopy and LAI = 5 represents a densely covered forest canopy in summer. With varying $a(z)$ values over the width of the modeled forests it is possible to realize different forest heights and forest drag forces in analogy to the complex and uneven shapes of forests.
Figure 1 shows the general shape of the local foliage density, used in the simulations of this study. There are two curves in Fig. 1 (a), one for LAI = 2 and one for LAI = 5, like it is mentioned before. For all simulations of the present study the values of the LAI = 5 curve were used for $a(z)$. Figure 1 (b) visualizes a $yz$-slice of the simulation mesh. With a colored contour the forest mesh is visible, which has been placed in the background mesh with the overlapping mesh technique chimera [14]. The colors show the $a(z)$ values of the forest for the easiest case with only variable $a(z)$ values in z-direction. The values above height are in analogy to the LAI = 5 curve in Fig. 1 (a). The x-, y- and z-geometries of these and of all following diagrams are normalized by the maximum forest height $H_F$.

### 3. Simulation setup

The forest simulations have been realized with a forest mesh, which has been placed in the background mesh. With a hole definition the chimera technique has been applied. Thus, to each cell of the mesh a drag force term could be assigned individually, to generate a forest, which is very similar to a real forest of the test site.

| Table 1: Simulation setup of the terrain simulations |
|-----------------------------------------------------|
| Parameter                        | Flat forest | Terrain | Terrain,F1 | Terrain,F2 |
| Cell number                      | ≈12.0 mio   | ≈41.3 mio | ≈42.0 mio | ≈42.8 mio |
| Varying $a(z)$                   | z-direction | -       | z-direction | yz-direction |

**Boundary conditions Background:**

- **Inflow:** Dirichlet
  - **Bottom:** No slip wall, Euler wall, Euler wall
  - **Outlet/sides:** Farfield, Farfield, Farfield

**Boundary conditions Forest:**

- **Bottom:** No slip wall, No slip wall, No slip wall
  - **Real:** Chimera, Chimera, Chimera

Table 1 lists the setup of the considered simulations. All simulations are unsteady Detached Eddy Simulations (DES) and the used turbulence model was the two equation model Menter
SST. For time discretization a dual-time stepping with 40 inner iterations per time step was used. In the present study four cases were analyzed. To explain the effect of the forest implementation and to clarify the results, a flat terrain forest was used. To investigate the behavior of forests in complex terrain, a wind tunnel model of the real terrain near Stötten at the Swabian Alb was chosen. For the simulation of the terrain three cases will be presented. The Terrain case represents the flow simulation of the terrain with neglect of forest vegetation. A uniform forest with a width of 12 $H_F$ and $a(z)$ values, which are only varying in z-direction, is described by case Terrain_F1. The values of $a(z)$ are identical to the LAI = 5 curve in Fig. 1 (a). The Terrain_F2 case illustrates a forest flow in complex terrain with a width of 28 $H_F$ and the local foliage density differs in y-direction, in addition to the different leaf area density in z-direction. Therefore, the forest drag force is not chosen constant over the width in this case. The general shape of the local foliage density remains the same but the $a(z)$ values and the forest height varies in y-direction. All forests are simulated with constant $a(z)$ values in x-direction. To generate the inflow, data are fed in at an inflow plane by a dirichlet boundary condition. With this boundary condition it is possible to feed in atmospheric turbulent inflow data by either measurement data or precursor simulations. On the other hand it is possible to generate synthetic turbulence by body forces. In the present case, the inflow data of wind tunnel measurements from the Institute of Aerodynamics and Gas Dynamics were used. The boundary layer was neutrally stratified with neglect of a roughness height $z_0$ at the ground. Therefore, in contrast to a real atmospheric boundary layer the wind speed is zero at the ground and not at a height equal to $z_0$. The mean wind profile is related to the power law approach with $\alpha = 0.27$ for a large roughness on the ground. The bottom surfaces are all treated as no slip walls. The top of the wind tunnel is simulated as inviscid Euler wall. The boundary layer is fully resolved with $y^+ \approx 1$, which implies a spacing of 0.0003 within the boundary layer in z-direction. Outside the boundary layer a grid cell size of $\approx 0.01$ is applied in xy-direction and $\approx 0.008$ in z-direction. For the simulations of the complex terrain model a Courant-Friedrichs-Lewy (CFL) number of 0.21 was used and the Reynolds number was set to $3.15 \cdot 10^6$.

4. Results

To give an explanation of the general impact of the new implemented forest model, the following section will discuss CFD results of flows within forests in flat terrain (Flat forest case). These results will be confirmed e.g. by wind tunnel measurements of flows within uniform forests in flat terrain of the University of Oxford in 1998 [15]. Afterwards, results of forests on a complex terrain wind tunnel model will be shown (Terrain_F1 & Terrain_F2 cases) and compared to the terrain with neglect of forest vegetation (Terrain case). Hence, it can be clarified how forest vegetation changes the inflow conditions of wind turbines. All geometries are normalized by the maximum forest height of the particular forest. All simulated uniform forests are realized with a local foliage density similar to the LAI = 5 curve in Fig. 1 (a). The simulated uneven forest shows an analogous shape of the local foliage density, with deviations of the tree height and deviations of the absolute values of $a(z)$ above the width (y-direction).

Figure 2 illustrates the effect of forest vegetation on the time averaged local flow field in flat terrain. With a fat dashed line, the area of the forest vegetation shall be highlighted. This forest is realized as uniform forest with constant $a(z)$ in xy-direction. The local flow field in axial direction $u$ in Fig. 2 (a) shows the deceleration of the wind speed within a forest. It is clearly visible that the wind speed retards differently above the height of the forest. This is in analogy to the local foliage density that varies above the height, which has been explained in Fig. 1. Therefore, the upper part of the forest slows down the wind stronger, than the lower part of the forest, because of different forest drag forces due to Eq. (1). Because of that the velocity profiles exhibit an inflection point within and downstream of a forest of this shape. By thin lines, representing constant wind speeds, the local foliage density shape within the forest.
Figure 2: Mean flow field of the Flat forest case. The forest is highlighted by a dashed line is represented in analogy to Fig. 1. Similar shapes of the velocity contour, were investigated by wind tunnel measurements at the University of Oxford measuring a uniform forest model via Laser Doppler Velocimetry [15]. They built tree models of the same shape and placed it uniformly in the wind tunnel. Thus, the setup is comparable to the uniform forest simulations in Fig 2. The mean velocity contour plots were not only similar for the axial velocity component \( u \), but also for the vertical velocity component \( w \) in Fig. 2 (b). The induced drag by a forest leading edge influences a flow distortion. Hence, a first large vertical velocity at the top of the forest occurs and a second flow deflection downwards in the lower part of the forest takes place, because of the maximum foliage densities near the canopy height of the forest. The same qualitative results are investigated by Dupont [16]. Dupont analyzed forests with several shapes of \( a(z) \) by LES simulations in flat terrain. He got similar plots of the velocities \( u \) and \( w \) with a comparable shape and comparable values of \( a(z) \). In Fig. 2 (a) a blockage effect with low wind speeds can be seen near the ground. Ruck et al. [17] described the same effect and argued with the overpressure the first trees generate because they “have to bear the highest wind loads”.

Figure 3: Time averaged flow field and velocity profiles in the Terrain case

Regarding the Terrain case without consideration of forest vegetation in Fig. 3, the contour of the axial velocity and velocity profiles near the ground can be seen for several x-positions of a cross cut at \( y / H_F = 0 \). In Fig. 3 (a) the speed up of the streamwise velocity can clearly be verified. On top of the terrain, where a flat plateau starts, the velocity is remarkable higher, than upstream of the hill. Figure 3 (b) visualizes several velocity profiles of the time averaged flow field. The speed up is clearly recognizable by the velocity profiles. Comparing the grey and the orange curve, it is remarkable that the plateau, which starts on top of the escarpment decreases the wind speed again. To sum this figure up, a large increase of the wind speed occurs...
due to the escarpment above the whole width of the terrain.

![yz-geometry of the uniform Terrain_F1 case](image1)

![yz-geometry of the uneven Terrain_F2 case](image2)

**Figure 4:** yz-geometries (grey) of the forest cases at x / H_F = 5 in streamwise direction

The geometrical extent of the forests of the Terrain_F1 and Terrain_F2 cases can be seen in Fig. 4, by a grey color. A uniform forest with almost the same tree height along the whole vegetation and a constant local foliage density a(z) in xy-direction is visualized in Fig. 2 (a). An uneven forest shape at the terrain is illustrated by Fig.4 (b). This Terrain_F2 case shows a forest, which spreads over a larger area in y-direction. Moreover, this forest has different tree heights in y-direction. The local foliage density of the forest in this case differs in yz-direction. Therefore, the leaf area density is only constant in x-direction. On top of that, Fig.4 gives an impression of the complex 3D shape of the terrain.

![Instantaneous situation of the forested complex terrain site (Terrain_F2)](image3)

**Figure 5:** Instantaneous situation of the forested complex terrain site (Terrain_F2)

Figure 5 illustrates the flow within the forested terrain site model. It’s a visualization of case Terrain_F2 and therefore the case with varying values of a(z) in yz-direction and constant values in x-direction. With black edges the geometrical size of the forest blocks of the mesh are visualized. The contour of height is shown in color and is highlighted by thin isolines of the same height. This should give an impression of the complexity of the terrain. Besides, some streamlines within and above the forest are shown. To explain the flow field in more detail, Fig. 5 is divided in four characteristic parts. Area 1 shows the free inflow of the terrain. The streamlines are colored equal to the velocity contour and give an impression about the wind
speed of the streamline in the respective area. Area 2 represents the area of the forested zone with the steepest slope. It’s shown that there are cross flow areas within the forest. These cross flows are due to the orography and to the different leaf area density above height and width of the forest. On top of the escarpment in the slice, that plots the velocity contour $u$ in area 3, a flow separation area can be seen. Thick black lines in the slice illustrate the 0 m/s velocity. Thus, there are two major areas of flow separation on top of the hill due to the forest and the complex orography. The slice on top of the hill with its shown velocity contours underlines the uneven shape of the forest above the width with different drag forces due to varying $a(z)$ values. This results in two areas of flow separation. In contrast, a planar flow separation would be expectable for a dense uniform forest. It has to be remarked that the complex 3D shape of the terrain also plays an important role, whether the flow separates downstream of the forest on top of the escarpment. Area 4 highlights the flow, which is undisturbed by the forest and gets accelerated by the steep slope in analogy to the flow in Fig. 3.

\[\text{Figure 6: Time averaged flow field and velocity profiles in the } \text{Terrain}_0 \text{ case}\]

Figure 6 shows important results of the complex terrain simulations within a uniform forest (Terrain_F1 case) that starts at $x / H_F = 0$ and ends at $x / H_F = 26$. Again the left figure shows the local flow field in axial direction and the right figure visualizes colored curves of velocity profiles at certain cuts of the flow field, which are marked in the same color. In comparison with Fig. 3 the forest at the escarpment is clearly obvious. Near the ground, reduced velocity values occur, due to the forest drag force. The dashed line in Fig. 6 (b) represents the maximum forest height $H_F$. It is remarkable that the velocity is decelerated within the forest area. An inflection point of the velocity profiles, which intensifies this impression, is visible in the first three velocity profiles. In previous studies this effect has also been analyzed by Belcher [18] and Dupont [16]. In comparison with Fig. 3 the grey and the orange curve show less wind speeds near the ground in the wake of the forest. Nevertheless, in this case no flow separation occurs downstream of the forest in the mean. Despite the reduction of the wind speed within the forest, on the average, the wind accelerates over the escarpment and reaches it’s maximum on top of the crest. This can be seen by the grey curve at $x / H_F = 29$. The flow on top of the orography does not separate, despite the forest drag. It has been suggested that this could occur due to cross flows within the forest, which lead to an airing of the low pressure area in the wake of the forest. Hence, preventing of flow separation is the concluding effect. Therefore, in the wake of the forest a velocity profile without an inflection point is formed with a low value of $u$ near the ground. Besides, the velocity profile shows a large gradient of $u$ above height, because of the acceleration over the escarpment of the terrain. Further downstream the speed up effect reduces. This becomes apparent by comparing the orange curve with the grey velocity profile. This effect is in analogy with the Terrain case without consideration of vegetation in Fig. 3.

Figure 7 shows the local flow field and the according velocity profiles in axial and vertical direction. The velocity profiles are cut from the same positions analogous to Fig. 3 and Fig. 6.
On top of the escarpment in the wake of the forest flow separation occurs in contrast to case *Terrain_F1*, because of the much larger width of this uneven forest. This area is highlighted by an isoline, which represents a velocity of 0 \( \text{m/s} \). Hence, it is obvious that the flow separation in Fig. 5 is not only instantaneous, but also appears on the average. The observation of flow separation on top of the terrain was also investigated by Knaus et al. [19]. With several methods Knaus studied the local flow field of a forested escarpment of the same wind energy test site. The grey curve in Fig. 7 (b) visualizes the position, where the flow separation area starts. This becomes apparent by the 0 \( \text{m/s} \) value of the axial velocity near the ground. The orange curve shows a position, which crosses the flow separation area, visible by negative \( u \) values near the ground. In general, the two main effects can be seen in analogy to the *Terrain_1* case. Within the forest, the wind is slowed down immediately, which leads to an inflection point of the axial velocity profiles. The other point is the speed up of the main flow due to the steep slope of the terrain. This effect is also visible within the forest. With increasing running length on the slope, the reduced wind speed within the forest becomes accelerated, but the shape of the velocity profiles remains almost the same.

This impact has been studied before by Belcher et al. [18], who investigated neutral flow over a forested Gaussian hill by LES simulations. The results of Belcher et al. [18], Finnigan et al. [5] and Ross et al. [20] are only applicable until reaching the top of the hill. They all investigated a Gaussian hill with a depression of the orography downwards after reaching the top. This results in other flow effects, which do not appear in the current terrain, because of the flat plateau on top of the terrain. The three curves within the forest at the positions \( x / H_F = [1,13,19] \) behave similar to the equivalent curves in Fig. 6 for the *Terrain_1* case. Minor differences result from slight deviations of the local foliage density \( a(z) \) in this cut. Hence, these three curves display again the characteristic inflection point for flows within forest canopies. Figure 7 (c) and (d) display the vertical flow field of the forested terrain model and its belonging vertical velocity profiles \( w \). Clearly remarkable is the large vertical velocity the steep slope induces to the flow field. A streak near the ground is visible, where the vertical velocity does not increase that much. The forest prevents a large flow inclination. At \( x / H_F = 0 \), where the forest starts,
an additional flow deflection upwards can be recognized in analogy to the effect in Fig. 2 (b). Due to the influence of the terrain model, this effect is strongly reduced but still noticeable. More detailed, the effects of the vertical velocity $w$ can be explained by Fig. 7 (d). The largest vertical velocities are feasible at the steepest position highlighted by the black curve at $x/H_F = 19$. The effect of vegetation on the vertical flow field is observable for each curve. Especially the orange curve downstream of the forest highlights the flow separation, which size appears to be similar to the forest height. This is an important fact for the geometrical extent of the flow separation area. Therefore, the height of this area could cut through the inflow area of the lower rotor half of a designated wind turbine at the test site. The bulge of the red curve is due to an additional vertical deflection of the flow at the leading edge, explained in Fig. 2 (b).

Figure 8: DES resolved scales in the respective area in % at $y/H_F = 0$

Figure 9: Normalized turbulent kinetic energy $k$ at $x/H_F = 19$

Figure 8 visualizes the DES resolved scales in the respective area in %. Typically for DES simulations the wall near boundary layer scales are mostly modeled by URANS. Same applies with respect to the forest at the steep slope. Above the near wall boundary layer and on top of the escarpment of the terrain over 90% of the scales are resolved.

$$DES_{res} = \frac{k_{res}}{k_{res} + k_{mod}}$$  \hspace{1cm} (3)

The resolved DES scales are calculated and plotted in analogy to Eq. (3). This equation shows a ratio of the resolved and modeled parts of the turbulent kinetic energy $k$. Figure 9 visualizes the turbulent kinetic energy profile $k$ above ground. The black curve illustrates the TKE at the $x/H_F = 19$ cut. The turbulent kinetic energy $k$ is normalized by a reference value at Height above ground / $H_F = 1$. It can be seen that the maximum of the turbulent kinetic energy $k$ occurs at forest height $H_F$. The reason for that is explained by Ruck et al. [17]. At the top edge of the canopy the Reynolds stresses reach their maximum due to shear stress emerging by mixing of two layers with different wind velocities: The reduced crown layer speed and the faster above canopy layer [17]. Within the forest, $k$ dissipates to a large amount because of the large canopy drag in the upper part of the forest [21]. Above the forest top, $k$ decreases again very quickly. In flat forest studies this decrease of $k$ is often observed in linear shape [12], [13]. In complex terrain, Ross [20] investigated the turbulent kinetic energy at a forested hill. His research highlights that $k$ increases at the slope near the summit because of large shear stress.

5. Conclusions

A forest vegetation model has been implemented in FLOWer and results were demonstrated in flat terrain for validation. On top of that, two cases of a forested terrain in a wind tunnel model were investigated. This wind tunnel model is a smaller scaled orography of the real test site of the WINSENT project. The forest drag force and therefore the reduction of the wind speed depends on the height $z$ and the latitude in $y$-direction, where the wind streams through the
uneven forest structure.

With the new implementation the influence of forested areas on the inflow conditions of wind turbines can be outlined. It has been described that on top of the terrain near the designated wind turbine position a flow separation area could occur with comparable size to the forest height. This flow separation or general reduced velocities downstream of the forest in combination with high inclination angles could result in load variation at the rotor plane. The lower rotor blade perceives significantly lower wind speeds in comparison with an upper rotor blade by cutting through the low speed wake of the forest. This effect could not only lead to load variation, but also to an additional wake deflection and to a different power gain of the wind turbine. Further, it has been investigated that forests on a steep slope, influence the local flow field both in axial and vertical direction. Besides, turbulence influences the inflow of wind turbines to a large amount as well, which has already been analyzed in previous projects at the test site. During upcoming tasks, these wind tunnel simulations will be applied in the real wind energy test site with the real inflow conditions. There the wind turbine will be included in its designated position. Moreover, the comparison of the simulation results with wind tunnel measurements at the IAG will be an upcoming work.

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