Effects of the canopy created velocity inflection in the wake development in a large wind turbine array

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Abstract. Large Eddy Simulations (LES) are carried out using OpenFOAM to investigate the canopy created velocity inflection in the wake development of a large wind turbine array. Simulations are performed for two cases with and without forest separately. Results of the simulations are further compared to clearly show the changes in the wake and turbulence structure due to the forest. Moreover, the actual mechanical shaft power produced by a single turbine in the array is calculated for both cases. Aerodynamic efficiency and power losses due to the forest are discussed as well.

1. Introduction

Wind energy covers 2.8% of total Finnish electricity consumption at the moment, [1]. Nowadays, wind power capacity in Finland is 883 MW, which is obtained by approximately 350 wind turbines. The Finnish government set the goal for wind energy industry to increase their production by 2020. The target is 6 TWh per year, equivalent to 2500 MW. By that time, the wind power can cover approximately 7% of the estimated electricity demand, [2]. Wind-farm arrangements are challenging in Finland, but at the same time, weather conditions are such that it is nearly constantly windy in Finland, especially in areas close to the coast. In Finland, 72% of the land area are covered with forest, and the forest areas often include hills and lakes. There are not many options where to install wind turbines. On one hand, the wind farm should be located close enough to the cities in order to decrease transfer, maintenance and grid connection costs. On the other hand, locations far enough from human habitation would be preferable in order to avoid disturbances such as noise. Thus, the chance that wind turbines will be placed in forest is very high. Therefore, the investing company needs to investigate wind conditions as well as wind-turbine wake behaviour in the real wind park site, possibly including forest and complex terrain, before the construction of the wind-farm is started. It can be made using field measurements and/or numerical simulations. Field measurements can be very expensive and time consuming. In contrary, numerical simulations can be relatively affordable. Nevertheless, many wind-energy companies do not trust yet in still developing but very promising Computational Fluid Dynamics (CFD) simulations.

There are certain well-known issues about the wind turbines located in the forested area. For example, Atmospheric Boundary Layer (ABL) profile starts recovering above three heights of

the forest canopy [3], and wake recovers faster downstream above the forest [4]. Wind conditions above forest have strong wind shear and increased turbulence levels which can lead to increased fatigue and shorter turbine life cycle [5]. A few wind tunnel studies were performed in order to better analyze how the canopy affects the wind energy production [4, 6]. Nevertheless, it has never been a subject of deep numerical analysis of turbine wake changes due to the forest created effects.

Current study demonstrates the potential of numerical simulations for studying wind and turbulence behaviour on a forested wind-park site. Wind and turbulence behaviours in wind parks located on flat terrain with and without forest are compared with each other. Large Eddy Simulations (LES) using "RK4ProjectionFoam" ([7, 8]) solver were carried out by OpenFOAM to investigate how the canopy affects the wind turbine wake development. At first, a turbine model validated earlier in [9] is implemented to perform simulation over a large wind turbine array. Then, the validated previously canopy model is used to carry out the LES over large wind turbine array placed in the forest. Results of the simulations are compared to clearly see the changes in the wake and turbulence structure due to the forest. Finally, the actual shaft power produced by a single turbine in the array is calculated for both cases, and aerodynamic efficiency and power losses due to the forest are discussed.

2. Numerical Modelling

The turbulent eddies larger than the grid-filter size are resolved directly on the computational grid, while the smaller eddies are modelled by a Sub-Grid Scale (SGS) model. In the current numerical set-up a one equation eddy viscosity SGS model is used.

There are many ways to numerically model turbine effects and loads, such as actuator disk, actuator line, actuator surface or rotation disk models. Following [10–12], Actuator Line Model (ACL) implemented in OpenFOAM (NREL SOWFA) has been used in this work for generating volume force from the wind turbines. Details of the ACL model can be found in [10–12]. In the current simulations we have modelled a wind turbine with a diameter (D) of 108 m. A hub height of the wind turbine employed in simulations (H) is 90 m. For the reference, turbine type ALSTOM ECO 110 with diameter of 110 m and hub heigth of 90 m is used. It has rated power $P_{rated} = 3$ MW at rated wind speed U_h^{rated} equal to 11.5 m/s. The airfoil type of the reference turbine blade is not known. Therefore, in this work the blade is represented by NACA0012 airfoil. The velocity calculated at the hub height U_h is 8.9 m/s. The tip-speed is 7.5 rpm.

The momentum source from the forest is represented by the following equation $\vec{f_i} = -C_D \alpha \, |\vec{u}| \, \vec{u_i}$, where C_D is the drag coefficient, α is leaf area density (LAD) and u is the local wind velocity, [13]. In the current simulation, canopy characteristics, such as, canopy drag coefficient $C_D = 0.15$ and LAD $\alpha(z)$, are taken from [13]. Leaf area index (LAI) in that case is equal to 2. The height of the forest (h) is 20 m.

The Reynolds number (Re_D) based on the rotor diameter D and the incoming velocity at the hub height U_h is 6.7×10^7. The computational domain is a rectangular block with the height of $4D$. The length and width of the computational domain are $15D$ and $10D$, correspondingly. The simulation over six wind turbines is performed on 4 m resolution grid. Computational grid, created using "blockMesh" utility in OpenFoam, consists of 56 424 600 finite element cells. Local refinement of the grid (up to 2 m) at the bottom part ($z < 2H$) of the computational domain is applied. The distance between the turbines in array is set to $5D$ in streamwise and spanwise directions. The simulation is performed with periodic inlet-outlet boundary conditions in OpenFoam by fixing the momentum source term g. In order to get approximately the same velocity at hub height U_h as in the case without forest, g is chosen to 0.004 m/s^2 and 0.0013 m/s^2 for cases with and without forest, respectively. The simple rough logarithmic ABL model is employed as the wall function model.

In both simulations the automatic time step by fixing the Courant number in the entire

domain to 0.1 is used. Therefore, the time step is approximately equal to 0.025 s in non-forest case and 0.019 s in case with forest. The flow is fully developed and averaged over more than 4.5 hours which is equivalent to approximately 2000 turbine rotations. In the following, the cases without and with forest are named as case-1 and case-2, respectively.

3. Results and Discussion

In the present study, LES is performed over six turbines located on flat terrain without forest (case-1) and with forest (case-2) separately in order to identify the effects created by the forest.

Figure 1 shows the contour plot of mean velocity on horizontal $x - y$ plane (top view) at turbine hub height ($z = H$) in the case without (left) and with (right) forest. In both cases, the mean velocity U is normalized by the hub height mean velocity (U_h). Here and below, U should be understood as the mean velocity in the windwise direction. From the illustrations in this figure, one can observe, that the wake disappears earlier in the case of the forest. The wake is already very weak at $x = 3D$ behind the turbine in case-2 and almost disappears after $x = 4D$ just in front of the following turbine. While in case-1 the wake does not disappear in front of the next turbine. This observation is in line with [6]. It can be also seen from the Figure 1 that wake in the case of the forest is wider in the spanwise direction compared to that in the case without the forest.
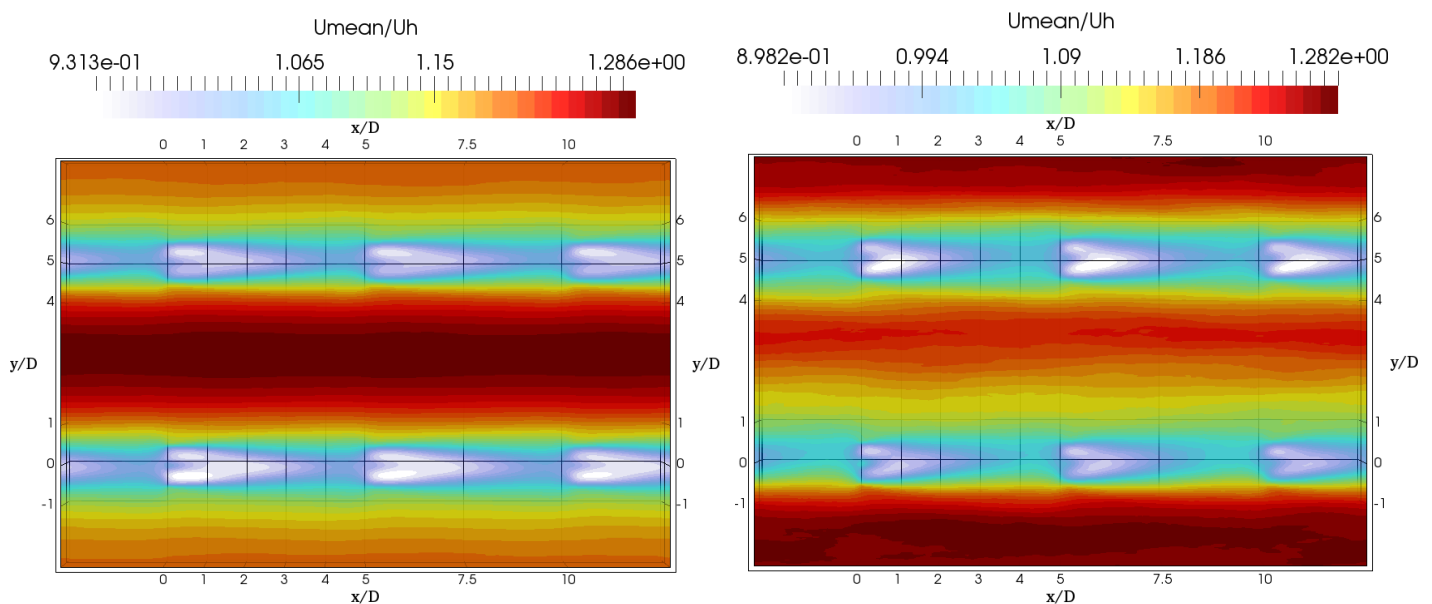
Figure 1. Top view of the normalized mean streamwise velocity in the cases without (left, case-1) and with forest (right, case-2)

Figure 2 represents the contour plot of vertical $x - z$ side view taken at first row of turbines ($y = 0$) without (top) and with (bottom) forest. It indicates similar results as in the Figure 1. Wake above the forest is not clearly seen in the picture. It apparently disappears within the rather strong forest-generated mean wind shear.

The vertical profiles of the normalized mean velocity at different streamwise locations after a turbine are presented in Figure 3 together with corresponding reference velocity profiles. The reference profiles are computed using otherwise identical setups but without the turbines. The reference profiles are visualised by dashed lines. The recovery of the wake velocity is faster in the case of forest, which proves the results described above. The flow below the lower-tip
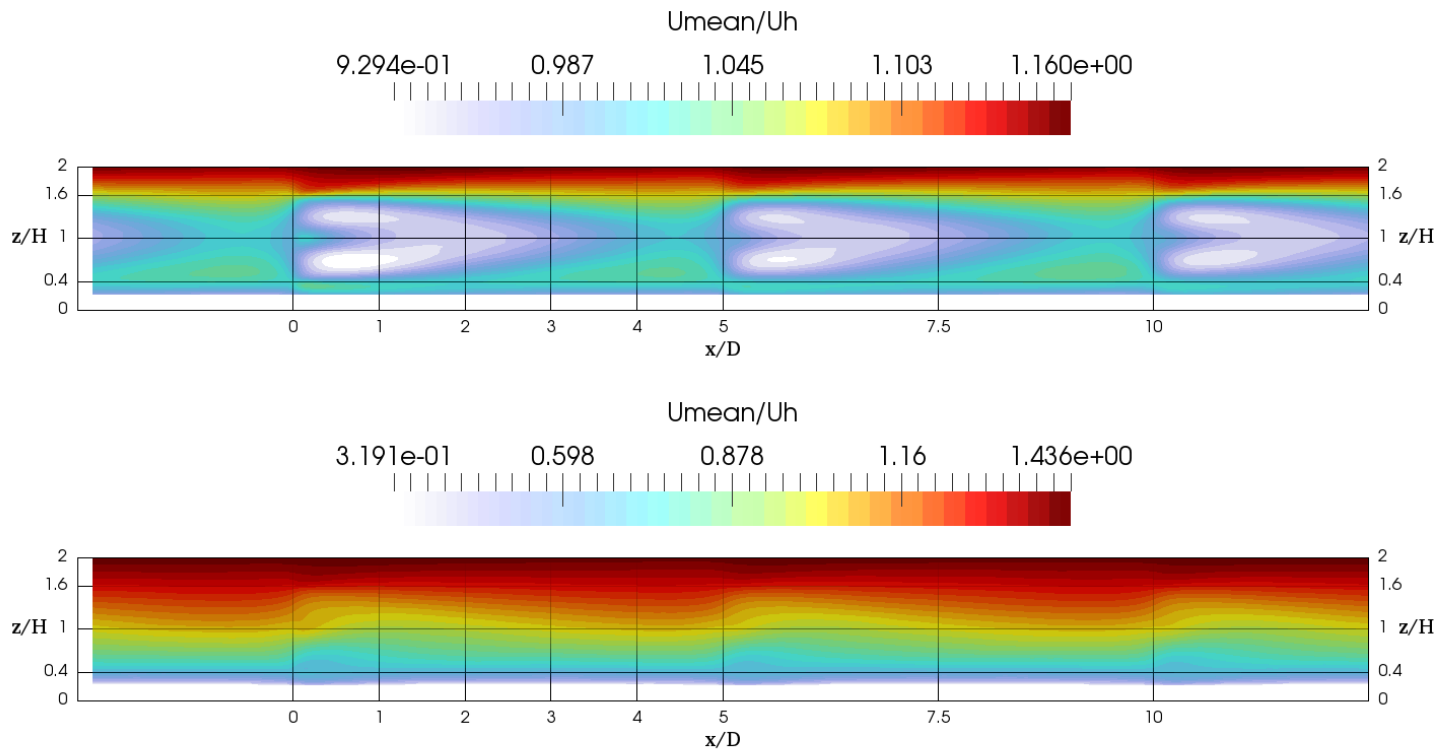
Figure 2. Side view of contours at first row of turbines ($y = 0$) of normalized mean streamwise velocity for cases without (top, case-1) and with forest (bottom, case-2)

Table 1. Velocity deficit due to turbine wakes calculated at turbine hub heigth ($z = H$) for different downstream positions $x = 0, 1, 2, 3, 4D$

|		0D	1D	2D	3D	4D
velocity deficit	forest	8.6%	15.7%	12.4%	8.5%	6%
due to wakes	nonForest	13%	16.8%	17%	15%	12%

($z = 0.4H$) is dominated by forest, as the wake profile coincides the reference wind profile at almost every location in the case with forest. The velocity deficit due to the turbine wakes $| U_{z=H}^{wake} - U_{z=H}^{ref} | / U_{z=H}^{ref} * 100\%$ is shown in Table 1. It shows the velocity deficit at five different streamwise locations. In the case with forest, the velocity deficit is two times smaller (6%) than the one in case without forest (12%) at position $x/D = 4$.

Following [4], turbulence intensity is defined as:

$$Tu = \frac{\langle u'^2 \rangle^{1/2}}{U_h^{local}}, \tag{1}$$

where u' is the velocity fluctuations in the windwise direction and the brackets $\langle \circ \rangle$ denote time averaging.

Figure 4 and Table 2 show the turbulence intensity deficit or excess due to the forest effects. Generally speaking, Tu is much higher in the case with forest, reaching more than double at 3 out of 5 locations compared to the case without forest. The calculated value is smaller than the one reported in [5], where turbulence intensity of windwise velocity component reaches 19.2% in the forest and 8.6% (or 131% of deficit) without forest at hub height of an imaginary turbine.
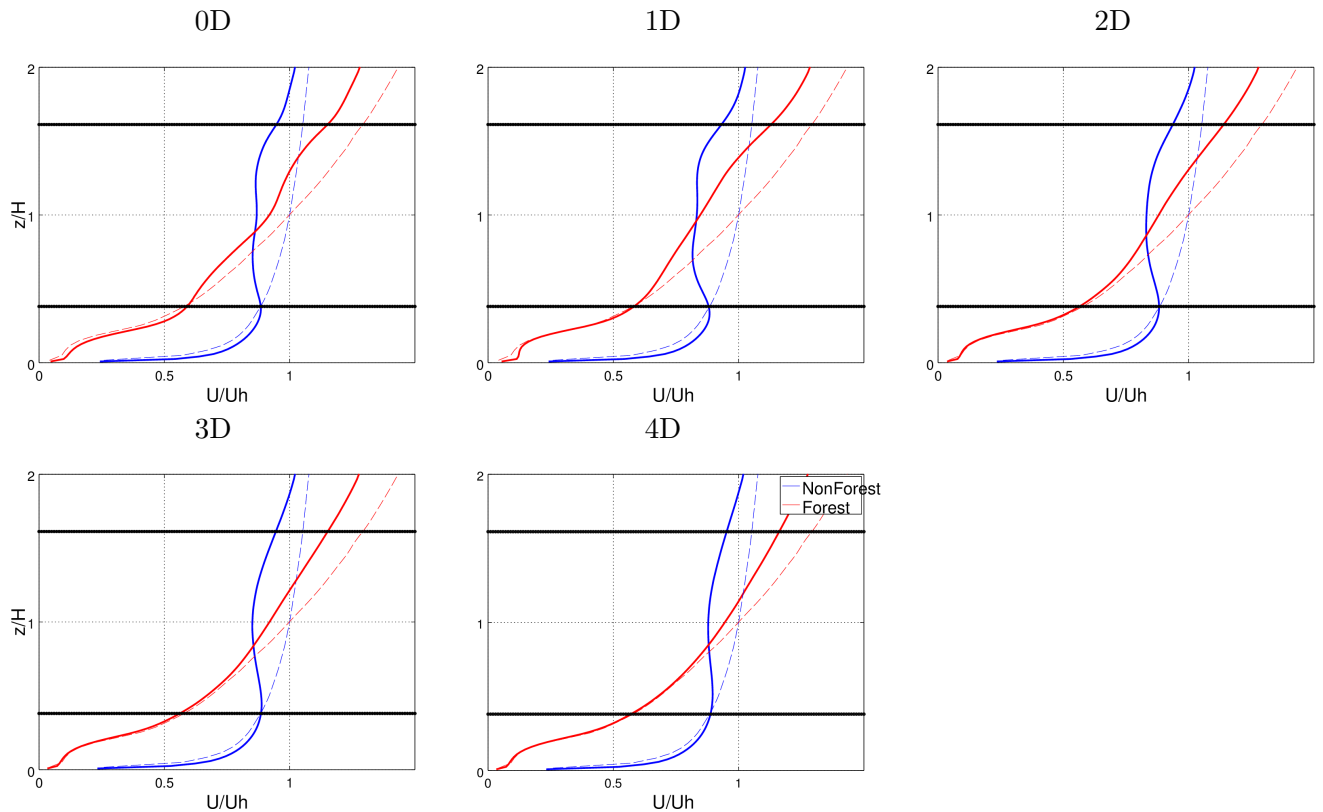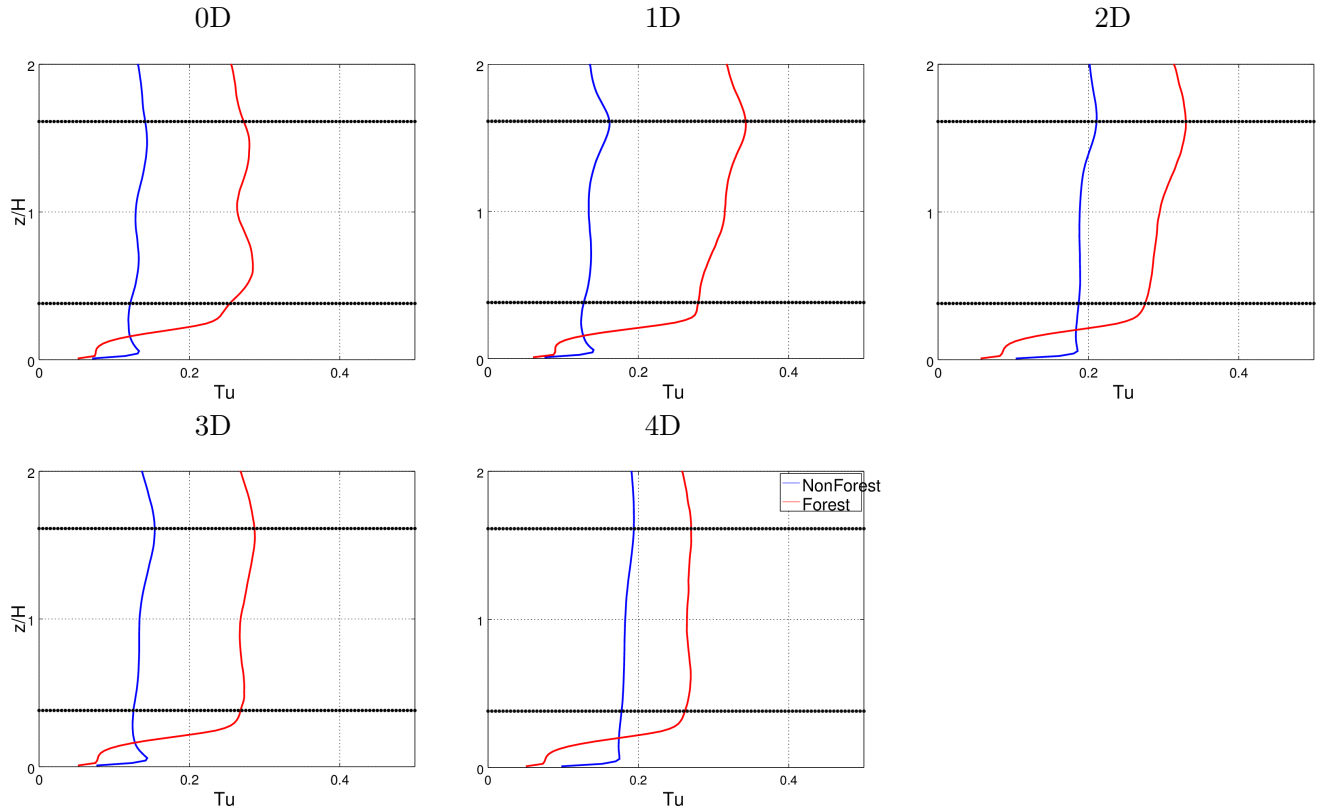
Figure 3. LES predicted normalized mean velocity U/U_h profiles (solid lines) at different streamwise locations in the cases without (case-1) and with forest (case-2). The profiles are also averaged at each respective locations of all 6 turbines. Broken lines (- -) indicate the LES predicted normalized mean streamwise velocity U^{ref}/U_h^{ref} profiles for the reference cases (non-forest and forest cases without turbines). Here and below, the black lines denote top ($z = H + D/2 = 1.6H$) and bottom tip ($z = H - D/2 = 0.4H$) of wind turbine

Table 2. Turbulence intensity deficit/excess due to the forest $\left| Tu_{z=H}^{forest} - Tu_{z=H}^{nonForest} \right| / Tu_{z=H}^{nonForest} * 100\%$ at turbine hub heigth ($z = H$) for different downstream positions $x = 0, 1, 2, 3, 4D$

	0D	1D	2D	3D	4D
Tu deficit	105%	135%	57%	100%	45%

At the same time, the obtained values of Tu (25-27%) at turbine location ($x/D = 0$) in the forest case are almost two times higher than the maximum value (16%) suggested by IEC for the wind turbine design, [5].

Figure 5 shows the longitudinal length-scale comparison between forest and non-forest cases (left) and validation of obtained results with the empirical expression by Counihan [6,14] $Lu_x = Bz^m$ for different roughness lengths (right). Figure 5 (left) represents the fact that both cases have turbulent structures that are large compared to the turbine diameter at the rotor disk height. However, in both cases, the structures are approximately equal to each other near the hub height, which is in contrary with the experiment [6]. This disagreement can be explained by the remarkable differences in set up of this work and that of Barlas et al. It

Figure 4. LES predicted normalized turbulence intensity Tu profiles at different streamwise locations in the cases without (case-1) and with the forest (case-2). The profiles are also averaged at each respective locations of all 6 turbines.

should be noticed that the experiment by Barlas et al. had only the upstream effect of forest (the forest edge is 3 m or $20D$ upstream the turbine) but the turbine was located outside the forest. Also the ratio H/h was small, only 1.37 while in this study it is 4.5. Further, the experiment [6] represents isolated single turbine wake, while the present simulation represent fully developed wake over infinitely long wind park due to the periodic boundary conditions used in the horizontal directions. In the LES prediction, apparently, with respect to non-forest surface (case-1), the turbulent length scale near the lower tip height is three times smaller while near the upper tip height it is 1.3 times larger in the case with forest. The smaller turbulent length scales around the lower part of the turbine disk imply more rapidly changing aerodynamic loads to the turbine in comparison with the non-forest case. This in combination with the remarkably higher turbulence intensity (Table 2) may have a strong impact to the fatigue life of the turbines. In Figure 5 (right plot), the numerical values from the forest case do not follow the lines but values from the non-forest case (at $z < H$) are located close to the theoretical line of the smallest roughness length ($z_0 = 0.01$). The inconsistency can be due to the turbine wakes which are not considered by Counihan theoretical law. It is also possible that this kind of forest-canopy flow is simply beyond the range of applicability of Counihan's law.

To calculate the value of so-called "global" shear (across the rotor disk area), the equation below is used:

$$\alpha = \frac{H}{U_h} \left(\frac{U_{tip}^{up} - U_{tip}^{low}}{z_{tip}^{up} - z_{tip}^{low}} \right). \tag{2}$$

The global value of $\alpha = 0.53$ obtained in the case with forest is ten times higher than the non-
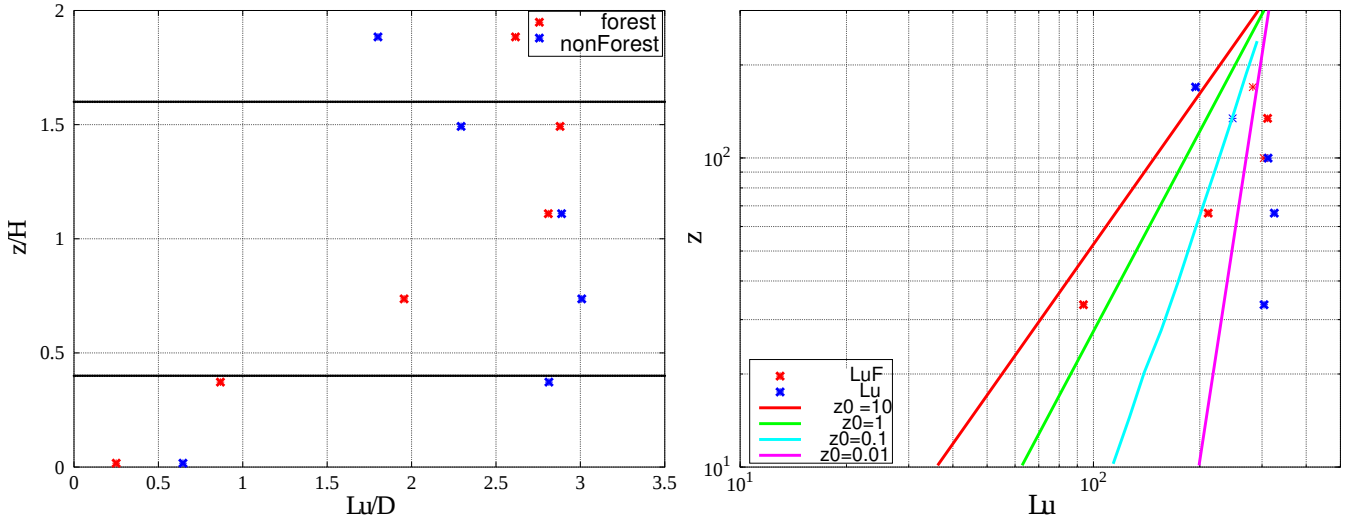
Figure 5. The integral length scale for cases without (case-1) and with the forest (case-2). Red and blue simbols represent the numerical values for cases with and without forest, but lines are obtained from the theoretical law for different roughness papameters $z_0 = 0.01, 0.1, 1, 10$m

forest value (case-1). This agrees very well with the value estimated at hub height in [4] ($\alpha = 0.5$). However, value in case-1 without forest (α=0.054) is four times smaller than in the [5] ($\alpha = 0.19$). This seems to be due to the turbine wake that extends much higher in case of forest as seen in Figure 3. The wake was not considered in the above mentioned LES study [5].

The time dependent power coefficient C_P is the ratio of the electrical power produced by the wind turbine divided by the wind power into the turbine (P_{avail}). Overall turbine efficiency (C_P) is defined as a product of aerodynamic (or turbine), mechanical and electrical efficiencies (η_t, η_m and η_e, correspondingly). The efficiency with which the blades convert available wind power into mechanical shaft power (P_{actual}, which could be predicted by the ACL model) is called the aerodynamic efficiency. Loss in the aerodynamic efficiency is the largest among all three efficiencies. At the same time, the aerodynamic efficiency is the only one predictable by the ACL model and the only efficiency which can be affected by the forest. Thus, for simplification, a system close to ideal, that is, mechanically and electrically efficient with only aerodynamic power loss, is considered in this paper. Therefore, the equation for time dependent power coefficient yields to equation (3):

$$C_P(t) = \frac{P_{actual}(t)}{P_{avail}}. \tag{3}$$

P_{avail} is the total available wind power:

$$P_{avail} = \frac{1}{2}\rho\pi R^2 U_{avail}^3, \tag{4}$$

where U_{avail}^3 is defined according to equation bellow:

$$U_{avail}^3 = \frac{1}{2R}\int_{H-R}^{H+R} U^3(z)dz, \tag{5}$$

where R is the radius of the rotor, $R = D/2$.

P_{actual} is the actual mechanical shaft power produced by one turbine. It is calculated as a mean of $P_{actual}(t)$ for more than 50 turbine rotations. The time history of the power coefficient

and power curve can be seen in Figure 6. Figures show power produced by the turbine in case without forest is larger than in case with forest which is because of slightly bigger wind speed (especially, in lower part $z < H$) in the non-forest case than in the forest. At the same time, the mean power coefficient is estimated to 0.29 and 0.25 in the case with and without forest, correspondingly. It is also obtained in the wind-tunnel experiment by [4] that C_P in case with forest is slightly larger (by 3%). It is assumed in [4] that the increase in C_P, as compared to the case without canopy, could be because of the increased turbulence, mean wind shear, or a combination of both. The fact, that our LES, performed at real scale with much higher Reynolds number, also gives similar increase in C_P in case of forest, suggests that the high wind shear might be the main reason of the increase.
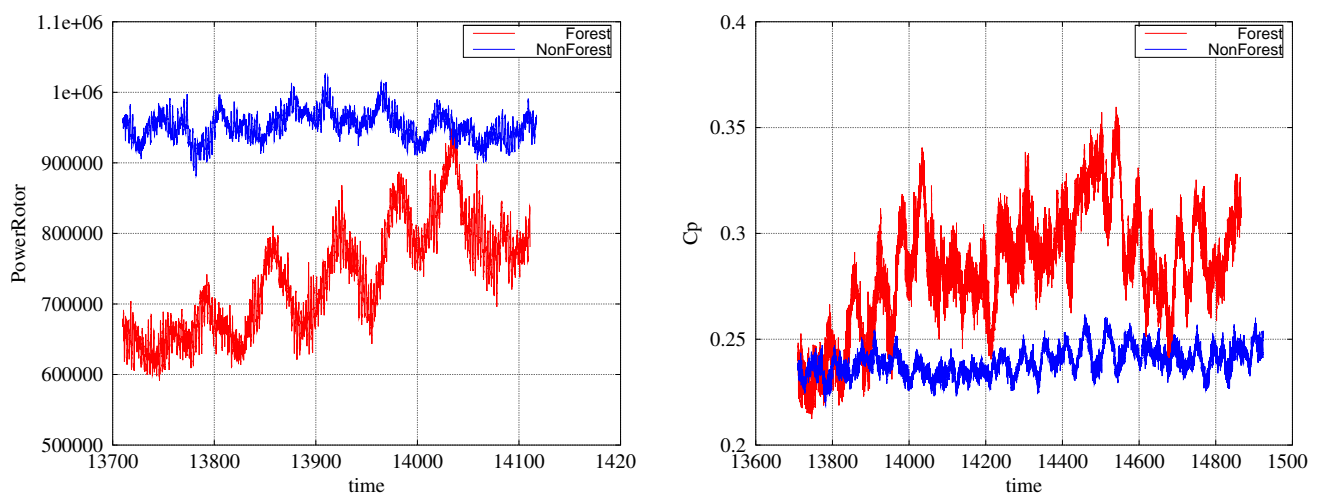
Figure 6. Time series for actual shaft power produced by the turbine (left) and power coefficient (right) for cases without (case-1) and with the forest (case-2)

Let us define the following quantities:
power loss due to forest

$$\left| \frac{P^{forest} - P^{nonForest}}{P^{nonForest}} \right| * 100\% \tag{6}$$

aerodynamic (turbine) power loss

$$\left| \frac{P_{actual} - P_{avail}}{P_{avail}} \right| * 100\% \tag{7}$$

Table 3. Comparison of power obtained in case-1 and case-2. Turbine losses for forest and non-forest cases and power losses due to the forest for available and actual power.

	forest	nonForest	losses due to forest
P_avail	2.78 MW	4.03 MW	31 %
P_actual	0.814 MW	0.989 MW	17.7 %
aerodynamic losses	70.8 %	75.5%	

The comparison of power obtained in case-1 and case-2, aerodynamic power losses and power losses due to the forest are represented in the Table 3. This table shows that aerodynamic loss in the case without forest is bigger than in the case with forest. Loss of actual shaft power due to the forest consists of only 17.7% while loss of the available power due to the forest is 31%.
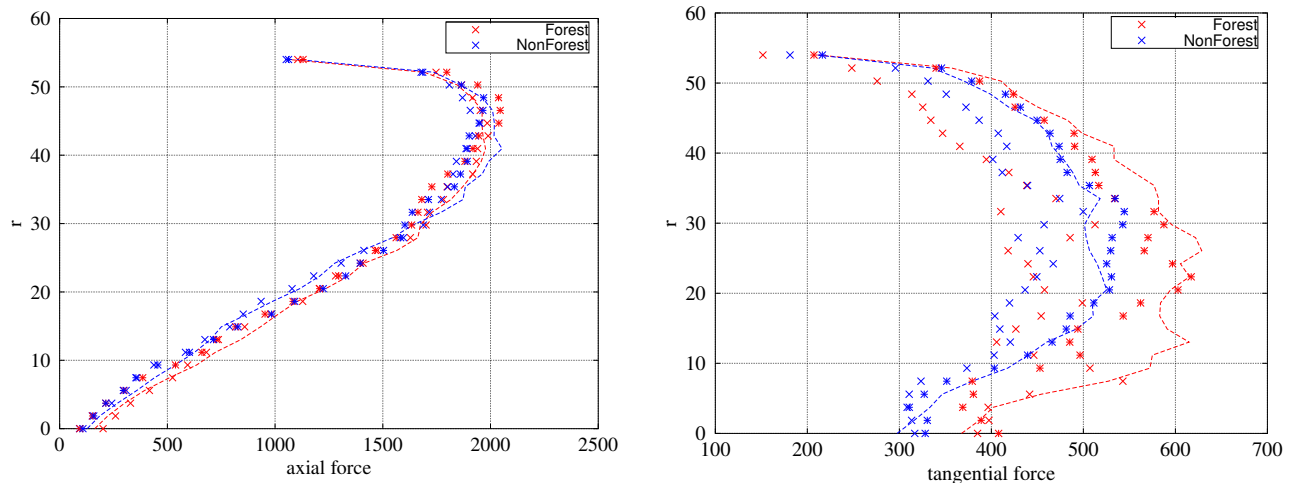
Figure 7. Axial (left) and tangential (right) forces calculated on turbine blades for cases with (case-1) and without forest (case-2) at certain azimuth ($\phi = 225^o$) Different symbols denotes different blades

Figure 7 shows the axial and tangential forces calculated on turbine blades for the cases without (case-1) and with forest (case-2) at certain azimuth ($\phi = 225^o$).It is clear that the axial force is in the same range in both cases. However, the tangential force is larger in the case of forest for two out of three blades at $\phi = 225^o$. When $\phi = 225^o$ then one of the blades is located in the upper-half plane ($z > H$) and the other two are in the lower-half plane ($z < H$). It is known, the tangential force provides torque which is related to power. Thus, similarly to power coefficient, very strong wind shear above the forest (in the lower-half plane) increases the tangential force in the case of forest in comparison to the case without forest (for two out of three blades).

4. Conclusions

In the current work, LES are carried out to model the flow behaviour in the large wind turbine array located on flat terrain with and without forest. Results of the simulations are compared to the existing wind tunnel measurements and other numerical studies. The obtained results agree very well with the available literature.

Results of the simulations show that the wake structure above/in the forest differs from the case without forest. The wakes from case-2 are wider in spanwise (as well as vertically) but shorter in streamwise directions than wakes from case-1. Taking into account this effect, the wind turbines above/in the forest can possibly be placed closer to each other than in the unforested site. However, it is seen from the side view of normalized mean streamwise velocity that the wake in case without forest is nearly symmetric in vertical direction over hub height. At the same time, the wake in case-2 moves into the forest, which basically means that the turbine is operating at very different wind conditions. That is, much stronger mean shear, much higher turbulence intensity and the smaller turbulent length scale, which were obtained in the current study for the case with forest in comparison to the non-forest case, can be harmful to the turbine and can reduce its life cycle.

On the other hand, the aerodynamic power loss in the case of forest is smaller but tangential force, calculated at the blades located in the lower-half plane, and power coefficient are bigger than they are in the case without forest. This indicates that performance of the turbine located in the forest is better mainly because of very strong mean wind shear and possibly because of increased turbulence intensity.

Therefore, the question of turbine location inside the forest will be further and deeply studied in the near future.

Acknowledgments

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