Large-Eddy Simulation of Porous-Like Canopy Forest Flows Using Real

Field Measurement Data for Wind Energy Application

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Abstract

Forests are an integral part of the world's landscape and are often characterized as regions with considerable potential on wind power. In order to take into account the existence of the forest for wind energy assessment, most of previous researches have implemented the drag force or roughness length approaches. However, the goal of this study is to model the forest with porous medium approach and investigate the mean wind and turbulence around porous-like-forest by means of Large Eddy Simulation (LES). For this purpose, *in situ* wind measurements, is obtained at Skinnarila forest, near the campus of Lappeenranta University of Technology, Finland.

Keywords: Wind Energy, LES, Canopy Flows, CFD, Porous Media, Experimental Validation.

Introduction

Predicting turbulence over the wind farms is highly important for wind energy assessment. Many sites with high wind speeds may not be a good candidate for wind energy production due to their high degree of turbulence. Forested terrain is an example to be given here. Nowadays, many onshore wind projects are being planned in or very close to forested landscapes due to its vast availability of wind and less number of inhabitants. Nevertheless, these regions are recognized with complex flow due to large variability of vertical and horizontal foliage distribution which induces the amount of turbulence within, above and around forested trees. To better understand the behavior of wind flow motions around forested area, extensive studies from site and laboratory experiments to numerical simulations have been carried out for many years [1,2,3]. Many researchers have examined how best they can evaluate and impose the effect of forest into numerical predictions of canopy flows. In Fabian et al. 2012 [4], the detailed representation of canopy derived from terrestrial laser scanning was used for LES to observe the aerodynamic influence of small scale plant distribution on clearing inside forest. The turbulent structures developed by a pine forest was numerically studied and validated with field data [5]. Here, the authors have utilized the measured mean vertical distribution of frontal leaf area density (LAD) for LES simulation and detected wakes behind the trunks. Similarly, LES were carried out using the drag force induced by trees under three different atmospheric conditions, namely stable, unstable and neutral [6]. In this work, the canopy model was implemented by considering a homogeneous forest with leaf area Index (LAI) very close to the measured *in situ* value.

Nevertheless for wind park simulations, the effect of canopy is often done by specifying a relationship between frontal LAD, local wind speed and drag coefficient which is added to the right hand side of momentum equations and turbulence models to account for turbulence length within forest [7,8,9]. It is important to note that measuring LAD is very costly in terms

of technology and time. Also, it is highly case dependent and may vary quite much from different forests.

In this work, we will model canopy forest with porous medium approach. In order to validate the porous LES results over forested and non/forested terrain, field measurements have been conducted at Skinnarila forest, near the campus of Lappeenranta University of Technology, Finland.

Methodology

Study Site:

The field measurement obtained at Skinnarila (near Lappeenranta University of Technology, about 7 km north-west of city of Lappeenranta in Finland) recorded wind continuously at 11 different heights from 24th of May till 6th of June, 2013. Part of the forest in which the experimental measurement took place was classified as a non-uniform plantation of pine trees. The average tree height was about 20 m at the forest edge and within.



Fig.1: Aerial view of Skinnarila forest with the two lidar devices (little diamonds) positioned at east and west.



Fig.2: Photo of terrain surface utilized for simulation. The black solid frame indicates the region of interest.

Fig.1 displays the aerial view of the investigated domain together with the two lidar devices positioned at 6770864N, 559016E (before forest) and 6770848 N, 558604 E (after forest)

which are marked as white-red diamond. As seen from the picture, these two devices are aligned according to the predominant wind direction which flows from Lake Saimaa through forest (east to west) with much less disturbances. Moreover, the terrain elevation above sea level is demonstrated in Fig. 2.

Data Selection:

In order to constrain our study under neutral meteorological conditions, the harmony weather forecast of every 3 hours data, including temperature and pressure for heights up to 3 km, provided by Finnish Meteorological Institute (FMI), has been used. Potential temperature, the most important and frequently used quantity in atmospheric science, together with velocity profiles limited to wind directions of around 90 have been plotted during the diurnal cycle for the period of measurement. As a result of boundary evolution presented by harmony potential temperature and velocity profiles, the dates satisfying the neutral atmospheric regime with lowest boundary layer thickness (less than 500 m) are identified and utilized over the real site measurement data. Again, based on availability of data at all 11 different heights, the decision has been made for 2nd day of June 2013 between 21:00 to 23:10 o'clock.

Numerical Descriptions:

In order to represent the forest effect into computational fluid dynamic (CFD) simulation, a porous media model is used. This is by additional sink/source term added to the right hand

side of the LES equations in the form $S = -\left(\frac{\mu}{k}U + C\frac{1}{2}\rho|U|U\right)$. This is the general form of

porous model composed of two parts: viscous and inertial drag loss terms, respectively. Here the ability of the medium to permit flow is denoted as k and the canopy inertial resistance coefficient as C. In the previous work [10] where porous parameterization study on flow through obstacles representing trees was investigated, we concluded the insignificant effect of permeability and porosity for high Reynolds number. By following this finding, the above sink term reduces to inertial drag loss term.

To solve the flow equations, the entire computational domain $(6 \times 2 \times 0.5 \text{ km}^3)$ is discretized into 11625000 of hexagonal grid cells with resolution of about 8 m in all three directions. The finite-volume method based un-structured code OpenFOAM is used in this study. In particular, the simulations are being carried out using our own in-house LES solver called "rk4ProjectionFoam" [11] recently implemented into OpenFOAM. For the numerical computations, the inflow boundary condition is defined according to the selected 2 hours and 10 minutes averaged horizontal velocity and wind directions recorded at 11 different heights of *in situ* measurement before the Skinnarila forest. To fully develop the turbulence structure, the so-called recycling technique [11] is employed at the inlet. The pressure is fixed to zero at outflow boundary and periodic boundary condition is assigned in the lateral sides. The symmetry boundary condition is set at the top surface. The logarithmic wall-function based on roughness-length is used to account the roughness effect.

Before employing LES, a series of Reynolds-averaged Navier-Stokes (RANS) simulations are carried out to parameterize the inertial resistance coefficient of porous-like forest. Afterwards, the most suitable coefficient is implemented into the porous model for the LES calculations. However, it is a good practice to perform LES without forest in order to better observe the turbulence induced by the forest.

Results

Field Experiments:

The 10 minutes averaged wind directions during 2 weeks of field measurement are shown in Fig. 3 for both locations: before (left) and after (right) forest. It can be seen that majority of wind is blowing into the forest approximately from east (close to east-north-east) at all 11 heights. However, the wind has turned its direction at lower heights (especially at 15 m) right after forest edge. This is shown more visibly in Fig. 4. Here the 2 weeks averaged data are plotted with height. Also, it is observed that the forest resistance causes the wind speed to slow down within forest.

Moreover, the 2 hours and 10 minutes averaged wind data over neutral atmospheric condition are plotted (see Fig. 5) which indeed depicts the drop of wind speed and a slight change in wind directions after vegetated area.



Fig. 3: Comparison of 2-weeks measured wind directions before (left) and after (right) forest at 11 heights.



Fig. 4: Comparison of two-weeks-averaged horizontal wind speed (left) and wind direction (right) at two positions: before (blue-line) and after (green-dashed line) forest.



Fig. 5: Comparison of about two hours averaged horizontal wind speed (left) and wind direction (right) at two positions: before (blue-line) and after (green-dashed line) forest.

Numerical Simulations:

Here, we report the preliminary results obtained from the first LES over the site shown in Fig. 2. In the following Figs. 6 and 7 the instantaneous and the 30-min time-averaged horizontal flow fields on the middle planes in stream-wise and span-wise directions are shown, respectively.



Fig. 6: Instantaneous horizontal flow fields on the stream-wise and span-wise planes.



Fig. 7: 30-min time-averaged horizontal flow fields on the stream-wise and span-wise planes.

Conclusions

Wind flow near and after forest edge was investigated in a field experiment using two light detection and ranging devices which were capable to record wind up to 150 m height from the ground. After forest, flow recirculation at lower heights was observed. Also, the wind

decelerated which indicates the existence of high resistance within forest due to distribution of vegetation.

Moreover, this paper has presented a procedure for post-processing a real field wind data in order to classify the involved atmospheric boundary condition based on harmony forecast data, during 2 weeks of measurement. As a result, the neutral weather condition was selected to be on 2nd day of June 2013 between 21:00 to 23:10 useful for our numerical simulations.

Here, turbulent flow over Skinnarila terrain which has a small hill is studied by means of LES. Due to high amount of CPU time required to run these simulation, the LES results over porous-like forest together with smooth-non-forested terrain will be compared with field data in near future.

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