Wind resource assessment in forested and complex terrain

Aurélien Chantelot[1], Didier Delaunay[1], Tristan Clarenc[1], Daouda Koulibaly[2]

[1] METEODYN 75, bd Alexandre Oyon, 72100 Le Mans, France
[2] SIIF ENERGIES France, 90 Esplanade du Général de Gaulle, 92933 Paris La Défense Cedex, France

ABSTRACT

Forested areas are increasingly of interest regarding wind farms development. Nevertheless, the trees perturbations on the flow generate high level turbulences and strong wind shears which could be unfavourable to wind turbine siting. An accurate estimation of these parameters is thus essential for the reliability of such wind farm projects.
CFD methods allow to take into account the impact of forests on the wind flow by the addition of drag terms or turbulence production in the conservation equations. Moreover, the complexity of terrain, often associated to these regions, can be fully taken into account by these methods.
In this paper, a new enhanced wind flow model of forested area is presented, calibrated and validated thanks to experimental results for a non-homogeneous canopy in complex terrain.
This model is implemented in the new release of the CFD software meteodyn WT 2.0.

1. INTRODUCTION

Approaches such as displacement height methods [1], have demonstrated their ability to compensate the canopy impact on the flow through a logarithmic/exponential wind profile within and above the canopy. However, these models are based on the assumption that the vertical gradient of the Reynolds stress is the only significant parameter which drives the flow. This assumption is not realistic as soon as the terrain topography or the atmospheric conditions becomes complex.
Indeed, under stable condition [2] , the vertical gradient of the Reynolds stress is small and therefore the horizontal pressure gradient, either associated with synoptic weather systems or baroclinic forcing due to even slight terrain slope is relatively large and cannot be ignored [3]. Moreover, modelling a forested hill using a roughness length parameterization may lead to a significant underestimation of the pressure drag and then of the wind shear above and behind the forest [4].

Most of the experimental validation of wind flow over forested areas are conducted in “ideal condition” (neutral to slightly unstable condition, homogeneity of the canopy, flat terrain) which are in accordance with the zero plane height displacement theory.

The theoretical basis of the new models implemented in the last version of the commercial software meteodyn WT 2.0 is presented.

Then, experimental and numerical results for a non-homogeneous canopy in complex terrain are presented.

2. THE MODELLING APPROACH

The principle of the CFD approach is to solve the full Reynolds-Averaged Navier-Stokes equations, which allows to computed detached and recirculating flows that occur over complex terrains. By integrating the more recent numerical techniques, and particularly a coupled multi-grid solver [5], meteodyn WT solves these equations in a very efficient way. Moreover the automatic mesh refinement strategy allows performing “typical windfarm size domain” computation without inherent problems of nesting techniques.

The drag effect of forests on the flow is directly computed trough an additional drag term inside the equation of motion.

Hence the momentum equations become:

$$\rho \frac{DU}{Dt} = -\nabla p + \nabla \tau - \rho C_d U|U|$$

where U is the Velocity, ρ the air density, p is the pressure, τ is the Reynolds stress, and C_d an effective drag coefficient described as the product of the vertical Leaf Area Density (LAD) and a tree-dependent drag coefficient. The LAD is assumed to be constant up to a height of 75% of the height of the forest canopy, than it is linearly decreasing up to free atmospheric flow conditions. Discussion on the drag coefficient parameter influence is presented in the test case hereafter.

The turbulence closure scheme is realized by the prognostic equation on the turbulent kinetic energy, *k,* and a mixing length approach for the diffusivity calculated from atmospheric conditions. Indeed, it was pointed out by Katul et al [6] that such schemes, often known as one-and-half order closure scheme models, give better results than the *k*-ε model concerning free atmosphere modelling.

The turbulence kinetic energy is then given by:

$$U_j \frac{\partial k}{\partial x_j} = P_k - \varepsilon + \frac{\partial}{\partial x_j}\left[\left(\frac{\nu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]$$

Where :

$$P_k = \nu_T \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial U_j}{\partial x_j}$$

$$\nu_T = k^{1/2} L_T$$

The length scale of turbulence L_T is depending on atmospheric stability (through the Richardson Flux number R_{if}), turbulent kinetic energy and whether the flow is inside the canopy or not [8].

The dissipation rate above the canopy is given by:

$$\varepsilon_c = C_\mu \nu_T k / {L_T}^2$$

and inside the canopy using the Wilson et al. sink term parameterization [7] :

$$\varepsilon_f = C_d |U| k$$

which allows modelling the quick dissipation of large scale turbulence inside the forest.
Then, the stability effects on turbulent viscosity are computed through the relationship given by Beckers (1995).

Hence we have:

$$L_T = \sqrt{2} S_m l$$

where

$$S_m = \begin{cases} 1.96 \dfrac{(0.1912 - R_{if})(0.2341 - R_{if})}{(1 - R_{if})(0.2231 - R_{if})}, R_{if} < 0.16 \\ 0.085,\ R_{if} \geq 0.16 \end{cases}$$

and, h being the canopy height and z the height above ground:

$$\frac{1}{l} = \begin{cases} \dfrac{1}{l_0} + \dfrac{1}{\alpha h}, \text{if } z/h < 1 \\ \dfrac{1}{l_0} + \dfrac{1}{\kappa(z-d)}, \text{if } z/h > 1 \end{cases}$$

With l_0=100m, d=2h/3, $\alpha = \kappa / 3$, $\kappa = 0.41$

The C_μ coefficient is given by:

$$C_\mu = \frac{2 S_m}{16.6}$$

3. THE FLOW PAST AN IDEAL FOREST

In this part are presented results of flow simulations over a domain containing a “theoretical” forest of dimension 500 m * 500 m with trees height equal to 30 m.

Computations were performed on a 2 km radius area, with a minimal resolution of the cell of 5 meters horizontally around the vertical profiles, and 2 meters vertically.

Both speed-up factors and turbulent intensity are plotted on vertical profiles placed in the symmetry plane of the forest:

- Upstream from the forest: P1 (250 m before).
- Inside the forest area: P2 (corresponding to the centre of the forest).
- Downstream from the forest: P3, P4, P5 (respectively, 100, 200, 800 m downstream from the forest).

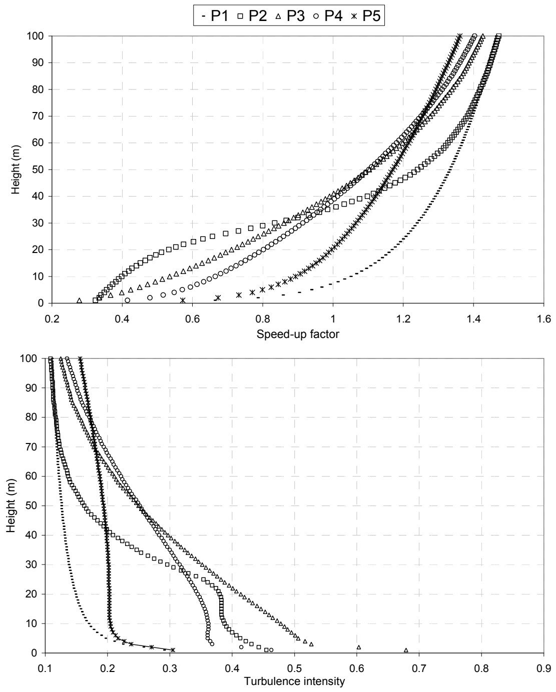

Figure 1: Vertical profiles of speed-up factors and turbulence intensity at several alongwind distances

Expected effects on the wind speed reduction and the increase of turbulence are well observed, showing the ability of the model to reproduce the physics of the phenomenon.

4. TEST SITE: FREYCINET LA TOUR

The “Freycinet La Tour” site (south of France) is instrumented by two met masts with a distance of one kilometre between each other. The 80 meters met mast (mast 4303) is located inside a pin forest and the 40 meters met mast (mast 4302) is on a low roughness area surrounded by 25-30m height pin forests at 100 m upstream in the wind directions between 45 deg. and 210 deg. Synchronous data are available from the 15th September 2005 to the 10th of January 2006.

The region is quite hilly as it is pointed out in figure 2. The main directional energy sector is centred around 150° .

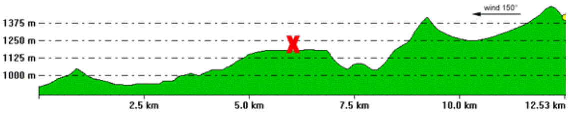

Figure 2: Topography profile of the site along the 330 deg. - 150 deg. axis

First analyses of the diurnal variation of the wind shear show that its variation is not significant through the day long (refer to figure 3). Due to the weakness of the synchronous data set, wind profile assessment will be conducted without distinction between neutral, or stable atmospheric cases.

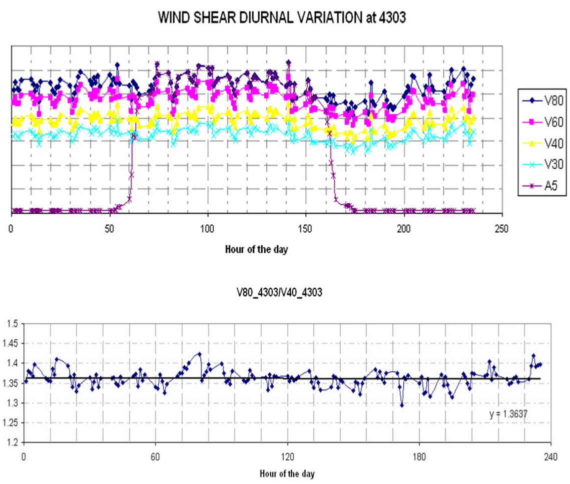

Figure 3: Measured wind shear variations at the test site

Computations were performed on a 7 km radius around the met masts locations, with a minimal resolution of the cell of 10 m horizontally and 5 m vertically. This leads to a 1.2 million cells grid domain. The computation time was 40 minutes with a Pentium(R) IV 2,8 Ghz.

First of all, comparison between various drag coefficient and experimental result are conducted. The drag coefficient is calibrated so as to reproduce the wind vertical profile at the met mast 4303. Figure 4 points out the importance of this parameter for the accuracy of the solution.

Eventually, a Cd = 0.005 has shown the best accordance with measurements.

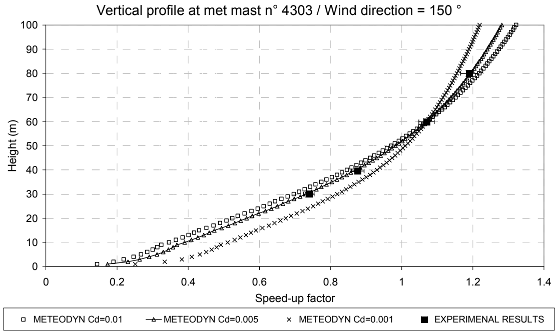

Figure 4: Vertical profiles of computed and measured mean wind speed at mast 4303

Using this parameterization of the forest drag coefficient, the computed vertical profile at the 80m met mast shows a good agreement with measurements. So far, the numerical results are inside the measurement uncertainties range.

The same experiment is conducted over the met mast 4302 vertical profile which is in the lee side of the forest. The profile is also well represented by the same value of C_d. This was expected as it is the same kind of forest which is concerned by the wind flow.

Hence a comparison between the speed-up factor calculated between the two anemometers is conducted. Figure 5 points out that the relation between the wind speed at the two sites is linear between 5m/s and 18 m/s. The slope of the linear regression with null intercept is equal to 1.09. The computations overestimate this value by 6 %. This error contains uncertainties due both to the complexity of the terrain and to the forest modelling. A more detailed description of the forest areas, and particularly concerning the spatial distribution of trees heights should probably still improve the estimation.

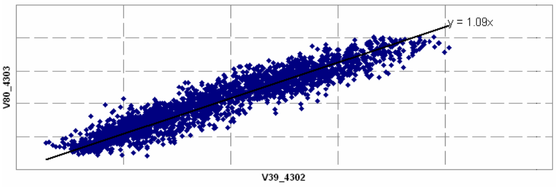

Figure 5: Correlation between the two met mast for 150° incoming wind speed

CONCLUSION

A methodology for the assessment of wind speed and wind shear in complex forested areas has been proposed. This methodology, associated with a CFD solving, allows to take into account both wind speed reductions and turbulence increase inside and downstream from the forests.

The calibration of the model is obtained by in-situ measurement. As more and more data become available, new developments will allow to precise characteristics of drag coefficient as a function of the kind and the density of trees.

The commercial software meteodyn WT 2.0, permits to apply this new modelling approach in a really cost effective way and adds valuable analyses to wind farm project.

ACKNOWLEDGEMENTS

We thanks ADEME (French Agency for Environment and Energy Management) for supporting the development of these researches.

REFERENCES

[1] Raupach, M.R., “Simplified Expressions for Vegetation Roughness length and zero plane displacement as functions of canopy height and area index”, Boundary-Layer-Meteorol.71, 211-216.

[2] Wyngaard, J., Kosovic, B., 1994, " Similarity of structure function parameters in the stably stratified boundary layer.", Boundary Layer Meteorol.28, 996-1001

[3] Xuhui Lee, "Air motion within and above forest vegetation in non-ideal conditions", Forest Ecology and management 135 (2000) 3-18 .

[4] Ross and Vosper, "Neutral turbulent flow over forested hills", Q. J. R Meteorol. Soc, 2005.

[5] Ferry M. (2002) "New features of the MIGAL solver", Proc. Of the Phoenics Users Int. Conf., Moscow, sept 2002

[6] Katul et al., "One and two equation models for canopy turbulence", Boundary-Layer Meteorol., 113, 81-109, 2004.

[7] Wilson J.D., Finnigan,J.J., Raupach, M.R., "A first order closure for disturbed plant-canopy flows, and its application to winds in a canopy on a ridge" , Q.J.R Meteorol. Soc., 124,705-732, 1998.

[8] P. J. Hurley, "An evaluation of several turbulence schemes for the prediction of mean and turbulent fields in complex terrain", Boundary-layer Meteorology, 83: 43-73, 1997.