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Development and Verification of CFD Models for Modeling Wind Conditions on Forested Wind Turbine Sites

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Summary

This paper describes a proposed CFD model to simulate the wind conditions on a forested site. The model introduces porous subdomains representing the forests in the terrain. Obtained simulation values are compared to field measurements in- and outside a forest. Initial results are very promising and in the future further model terms will be implemented in order to increase accuracy of the model.

Abstract

More and more sites are located in the vicinity of forested areas. As a consequence accurate simulations of the wind conditions near forests are becoming increasingly important in the wind turbine industry. Knowledge of wind speed and turbulence quantities gives valuable information regarding e.g. expected energy yield and turbine loads.

In order to predict the wind conditions at a forested wind turbine site a CFD model utilizing porous subdomains has been developed. The model results have been compared to measurement data collected in- and outside a forested area on Falster Island, Denmark [1].

A 2D model introducing porosity has been implemented in ANSYS CFX using the k-ω SST turbulence model [2]. This is done by enabling a permeability term in subdomains representing forested terrain. The permeability term in the model expression varies with tree height in order to capture the correct porosity through the forest domain.

The Forest Model

The developed CFD model introduces subdomains representing forested areas into the terrain of interest. In order to simulate the forest resistance more correctly measurements of the Leaf Area Density (LAD) taken from the Falster forest [1] have been used to fit an expression dependent on tree height for both summer (leaves on) and winter (leaves off) conditions.

Equation 1 describes the LAD distribution with height, z [3].

$$LAD(z) = LAD_{\max}\left(\frac{H - z_{\max}}{H - z}\right)^{n} \exp\left[n\left(1 - \frac{H - z_{\max}}{H - z}\right)\right] \qquad (1)$$

where LAD_{max} is the maximum LAD of the tree, z_{max} is the vertical location of LAD_{max}, H is the average height of the forest and n is a calibration constant dependent on the height.

The fitted expression used in the model is plotted in Figure 1.

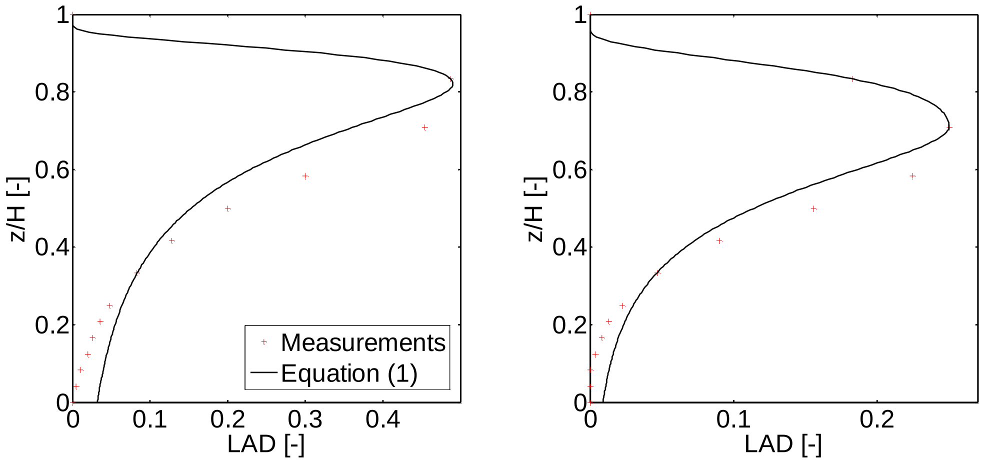

Figure 1 – The fitted expression, Eq. 1, compared to the obtained measurements of LAD.

Instead of introducing a variable LAD value the proposed model applies a permeability dependent on height in the forested subdomains. Eq. 1 is used inversely with constants fitted for the Falster forest conditions [1,4] such that a high LAD value results in low porosity and low LAD results in high porosity.

Experimental Measurements

The proposed model has been compared with a measurement campaign carried out by Risø National Laboratory [1] during 2008. The forest site located on Falster Island, Denmark was setup with 2 met masts positioned approximately 40m outside (MM1) and inside (MM2) a beech forest near the western forest edge. The forest is on average 24m high. Both masts were instrumented with sonic anemometers in various heights.

An aerial overview of the Falster forest is seen in Figure 2 and the heights of the sonic anemometers are seen in Table 1.

Figure 2 – Falster forest with positions of met masts.

MM1	MM2
-	6m
11m	11m
-	18m
20m	-
-	24m
-	29m
30m	-
-	36m
45m	45m

Table 1 – Vertical location of the sonic anemometers.

The collected data has been divided into a summer and winter batch corresponding to a leaves on and leaves off situation, respectively. Furthermore the data has been divided into a direction bin of 30° centered around 297.6°, i.e. a west-nort h-westerly wind direction, which is orthogonal to the western forest edge. In addition to that only neutral atmospheric conditions are considered. For that purpose the Obukhov-length, L, is utilized and the atmospheric conditions are regarded as being neutral for $-1 < \zeta < 0.7$, where $\zeta = z/L$. Hereafter the mean values of wind speed and turbulence quantities have been calculated for the purpose of comparison with the CFD model results.

For further information on the experiment the reader is referred to [1].

Results and Discussion

All presented plots in this section are normalized with simulated values 10 forest heights upstream of the forest edge at 45m height.

Plots of normalized wind shear and turbulent kinetic energy are presented in Figure 3.

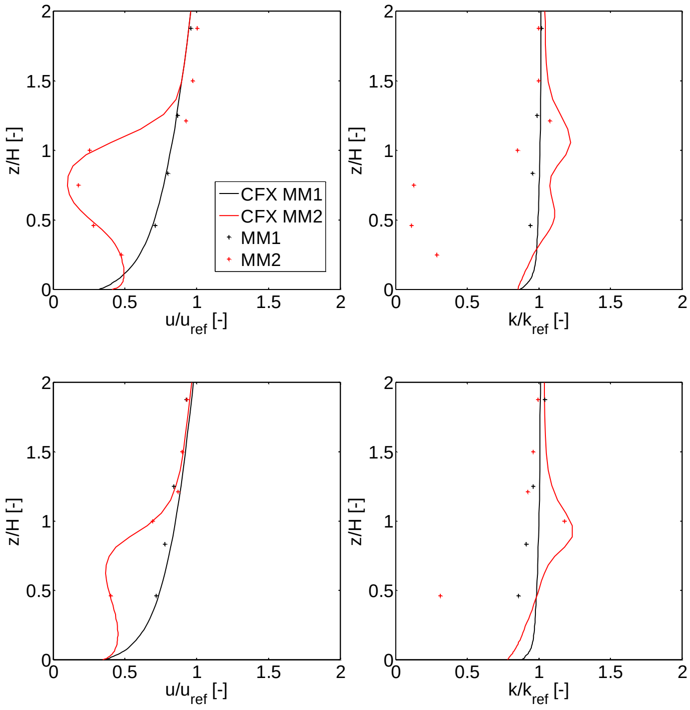

Figure 3 – Plots of vertical wind shear (left) and turbulent kinetic energy (right) for summer (top) and winter conditions (bottom).

In Figure 3 the height is normalized using the forest height as reference. The model results are extracted at the same locations as the met masts in the real terrain.

It is seen that the wind shear is captured very well in both summer and winter conditions. Furthermore it is observed that the wind speed is reduced dramatically inside the forest canopy as compared to outside the forest due to the resistance exerted by the forest. The appearance of the wind shear in front of the forest edge resembles a logarithmic velocity profile for neutral atmospheric conditions while the model curve and measurements inside the canopy corresponds with the reported trends in [5].

The turbulent kinetic energy is not predicted quite as accurately as the shear inside the canopy. This is especially true for the summer conditions where many leaves on the trees result in a larger flow resistance than during the leafless winter season. Clearly, further adjustment of the permeability is needed in order to enhance the accuracy of the model.

The observed decay of turbulent kinetic energy is delayed inside the forest as compared to the measurements. Implementation of source terms for dissipation of the turbulent quantities is currently under investigation and it is hoped that this will improve the prediction of the flow.

Figure 4 presents plots of wind speed and turbulent kinetic energy in a horizontal direction parallel to the wind direction. The model values are extracted at 45m height since both MM1 and MM2 are instrumented with anemometers in this height.

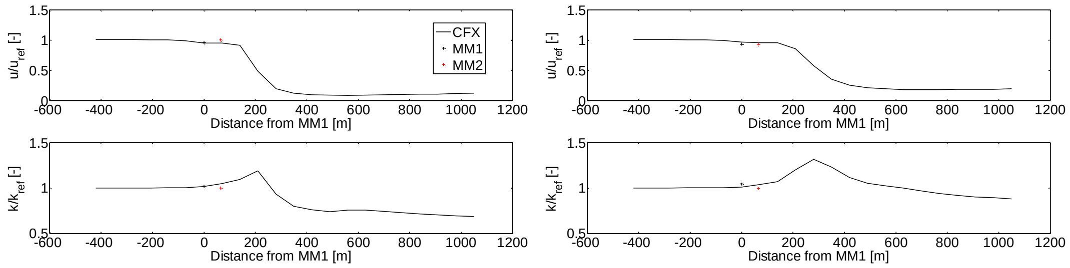

Figure 4 – Normalized values of wind speed and turbulent kinetic energy extracted at 45m in a direction parallel to the wind compared to measurements for summer (left) and winter conditions (right).

With only one measurement mast downstream of the forest edge it is difficult to relate the measurements to the model results but one would expect a slight decrease in wind speed until immediately in front of the forest. After this a speedup due to the presence of the forest obstacle would be expected.

It is seen how the model predicts a slightly decelerated wind speed in front of the forest edge while after approximately 150-200m downstream the wind speed is heavily retarded. This could indicate an overly high flow resistance caused by a too small value of permeability implemented inside the forest canopy.

For the case of turbulent kinetic energy it is observed how the model predicts an increase in turbulence approximately 200-300m downstream of the forest edge. This peak value is related to the not fully correct deceleration of the flow above the canopy downstream of MM2.

Contour plots from CFX in summer conditions are presented in Figure 5.

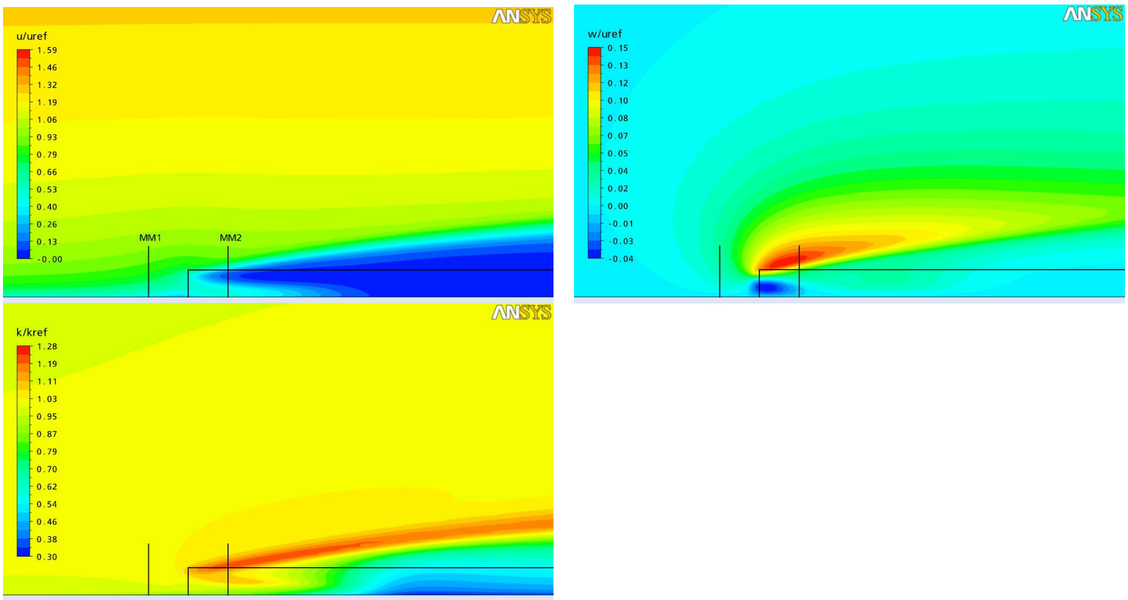

Figure 5 – CFX contour plots of u/u$_{ref}$ (top left), w/u$_{ref}$ (top right) and k/k$_{ref}$ (bottom left) for summer conditions. Met mast positions and location of the forest are included. Wind direction is from left to right.

The top left plot in Figure 5 depicts contours of u, the velocity component in Cartesian x-direction, normalized with a reference value taken 10 forest heights upstream of the forest, at a height of 45m.

From Figure 5 is should be noted how the flow deceleration occurs in front of the forest edge although a strong slow down is also observed inside the canopy area. The profile of the deceleration curve inside the canopy is seen to originate from the LAD-related permeability distribution, cf. Figure 1, where the flow resistance is greater in the leaf rich crown part of the tree as opposed to the lower bare trunk.

Secondly, downstream of MM2 the velocity values are very low and the strongly decelerated area reaches relatively far above the canopy.

The former could indicate that the flow resistance in the front part of the forest is not large enough to create the expected speed up immediately in front of and above the forest edge, while on the other hand the latter could indicate that the flow resistance is actually too large inside the canopy, i.e. the permeability downstream of the forest edge should vary.

The plot of w, velocity component in z-direction, clearly shows how the flow lifts off when approaching the forest edge but again this happens a bit later than expected.

For the turbulence kinetic energy, k, the mentioned delay is visible here as well and the strong decay of turbulence downstream and inside the canopy again indicates a too large resistance.

It should be noted though that Risø National Laboratory themselves are not fully convinced that the measurements collected inside the canopy, i.e. from MM2 up to 24m, are measured correctly. This is due to the presence of leaves in the immediate vicinity of the sonic anemometers. Because of this uncertainty it is yet not fully clear to what extent the model needs calibration in order to perform better.

The same contour plots as Figure 5 are shown in Figure 6 only for the winter conditions.

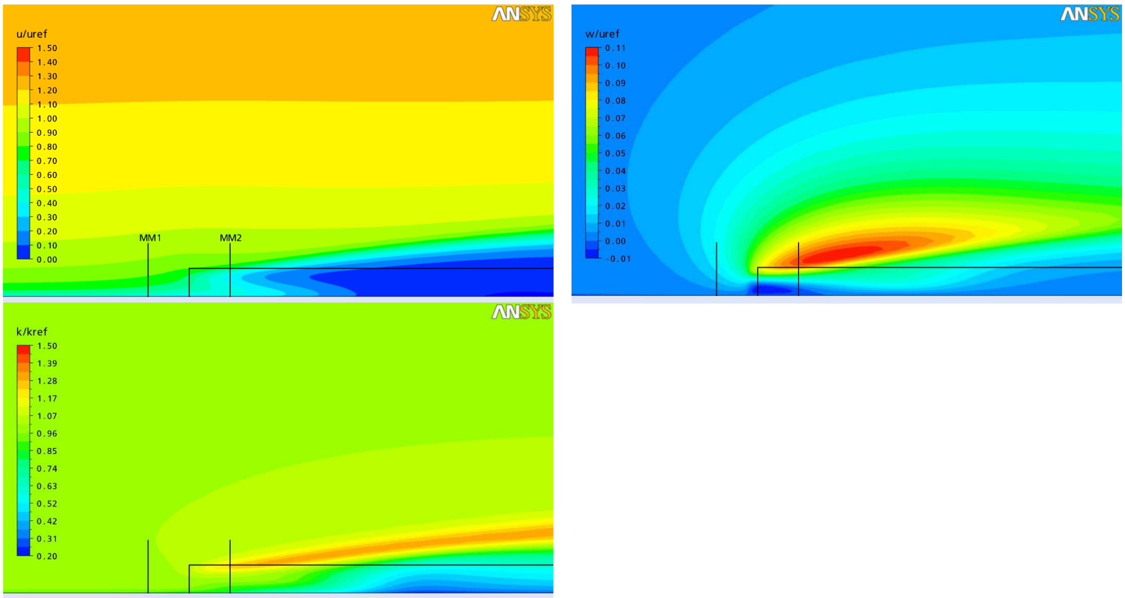

Figure 6 - CFX contour plots of u/u_{ref} (top left), w/u_{ref} (top right) and k/k_{ref} (bottom left) for winter conditions. Met mast positions and location of the forest are included. Wind direction is from left to right.

In general the discussion for the summer contour plots apply for the winter plots as well. The general tendencies are similar but for the winter conditions the observed delay in flow response to the resistance exerted by the forest is even greater due to the higher permeability compared to the summer conditions. This is caused by the difference in LAD for summer and winter, cf. Figure 1.

Conclusion

A 2D CFD model has been setup to simulate the wind shear and turbulence quantities generated in the vicinity of a forest.

The modelled shear both upstream and inside the forest corresponds well with measurements from a forest on the Island of Falster in Denmark.

The decay of turbulent kinetic energy inside the forest is delayed in the model as compared to the measurements. Work is currently ongoing on formulating additional source terms for the dissipation of turbulent kinetic energy inside the forest.

The modelled flow deceleration downstream of the forest edge is exaggerated compared to the measurements. This could indicate an overly high flow resistance in the forested subdomain, where the likely cause is the level of permeability which will be examined in the future.

Other models are currently being investigated such as the momentum source model of [5].

Testing in 3D is ongoing.

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