New Model for Calculating Intensities of Turbulence in the Wake of Wind-Turbines

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1. Introduction

First measurements of load-spectra within Off-Shore-Windfarms [5,6] and disappointing yields of in-land on-shore farms clearly show the necessity, to predict power as well load spectra more accurate then now. The most important input-parameters are:

- Extension of the wake-deficient (for estimation of farm efficiency).
- Turbulent intensities in the wake (for prediction of fatigue loads).

It is very tempting to use the methods of Computational Fluid Dynamics (CFD) for the prediction of the above cited quantities. However, for resolving all the relevant details of the flow the mesh must be extremely fine – up to several millions hexahedral cells have been used for example in [7]. Despite this enormous effort the success is limited to approximately 10% accuracy of power-prediction - esp. in the stalled regions of the blade - due to the intrinsic inaccuracy of known turbulence-models. In contrast to that the well-known and very popular Blade-Element-Momentum theory based methods coded into the PROP code of Wilson et.al. for example gives useful results only when feded with “3D-corrected” (not to say: fitted) 2D aerodynamic polar data for the used profiles.

In our approach based on the concepts of actuator disk theory we try to combine to some extent both methods and to include generation and development of turbulence. During an internal meeting on problems of Off-shore windfarm design one of us (FR) suggested these investigations. MR accomplished most of the work and APS took care of the workframe as and acts as a supervisor.

2. Description of used Model

Our model is 2D-axisymmetric and the whole wind-turbine is modelled as a disk in which radial resolved body forces are put into the flow field which are computed via 2D lift and drag data of Profiles (for example the well-known NACA 634xx-series or those from FFA). Insofar there is no difference to BEM but outside the wind-turbine-disk we calculate the whole flow-field by solving Euler’s equation with a standard commercial CFD-package (CFX or FLUENT). Therefore we have radial velocity-components included and no tip-correction is necessary. Complicated arrangements like diffusors [1] or other non-standard arrangements are simple to include.

For turbulence effects to be included we have to decide which of the numerous models available we want to use [9]. For reasons of simplicity we decided to use an ordinary k-epsilon two-equation-model where the sources for k were coupled to the local thrust-coefficient of the wind turbine blade. In contrast to its conceptual simplicity this model is much more sophisticated than models implemented in wind-farm design-codes[2,3,4]. Most of them use only coupling to the integral thrust-coefficient (see. Fig. 1).

A summary of important relations and details of the k-epsilon-turbulence model is shown in fig.2.
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3. Results
Most of the presented work was performed from M.P. during a semester stay at the UAS Kiel. To have an impression of the consequences of our new model we used the well-documented ARA48 blade [9], which has also been served as example-case in other areas of wind-turbine aerodynamics.

Fig. 3 shows the typical wake-shape for near design-point operation. Because we used BEM for velocity-force coupling we are sure that integral parameters like thrust and power is in accordance with design or measured data. Therefore we can trust that the wake-spreading has the right shape. Because convective effects are rather important in wake- and turbulence development – also in the clearly visible shear layer representing the wake’s border – this has to be modeled in a consistent manner.

\[
\begin{align*}
  u &= U + u' \\
  U &= \langle u \rangle \\
  k &= \frac{1}{2} \langle u'_\alpha \cdot u'_\alpha \rangle \\
  S_{\alpha\beta} &= \frac{1}{2} \left( \partial_\beta U_\alpha + \partial_\alpha U_\beta \right) \\
  \tau_{\alpha\beta} &= \frac{2}{3} k \delta_{\alpha\beta} - \nu T S_{\alpha\beta} \\
  \nu T &= C_\mu \frac{k^2}{\varepsilon} \\
  \partial_t k + U_\alpha \partial_\alpha k &= \tau_{\alpha\beta} \partial_\beta U_\alpha - \varepsilon + \partial_\alpha \left( \frac{\nu T}{\sigma_k} \partial_\alpha k \right) \\
  C_\mu &= 0.09 \quad \sigma_k = 1.0 \\
  C_{\epsilon_1} &= 1,44 \quad \sigma_\epsilon = 1,3 \quad C_{\epsilon_2} = 1,92 \\
  I &= \frac{\sqrt{2k/3}}{U}
\end{align*}
\]

Figure 2: Some Relations within the k-epsilon turbulence model [8].

Fig. 4 and 5 show that both other velocity components are important and may not be neglected. The corresponding turbulent kinetic energy k which is related to the turbulence intensity I via the formula in the first row of Fig. 2. (U is the ensemble averaged velocity) is shown in Fig. 6.

Figure 3: Wake (total velocity) development for \(v_{in} = 8\) m/s

Figure 4: \(v(\text{circumferential})\) velocity for \(v_{in} = 8\) m/s

Figure 5: \(w(\text{radial})\) velocity for \(v_{in} = 8\) m/s

Figure 6: Wake (turbulent kinetic energy) development for \(v_{in} = 8\) m/s, \(k=2\) corresponds approx. to \(I = 15\%\)
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It can be clearly seen that most of the turbulence is generated close to the tip and that it is convected downstream with considerably spreading. Turbulence levels not smaller that 7% exists even at the (too small chosen) outlet-boundary of the calculational area. Various different case have been estimated. We present only one additional case for the low-wind off-design case:

4. Summary

Therefore it can be recommended that large distances our new model developed from a combination of actuator disk concepts and CFD put the extra production of turbulence in form of local – i.e. radial resolved thrust-coefficient. Therefore the consequences can be studied in more details. The description of the convective transport and decay the global flow parameters (development of the wake shape) have to be accurate.

As a first application we used a three bladed wind turbine with ARA48 blades. In all cases strong extra-production and transport far downstream can be seen. As a recommendation the distance of more than five diamettes between turbines should be used at least at critical places.

5. Outlook

To improve accuracy and performance the most empirical part of the model, the source for k has to be based on more first-principle assumptions. Because turbulence is generated in the boundary layer [10] of the blades, these mechanisms have to be investigated carefully. 3D effects like rolling up of the vortex-sheet to the well-known trailing vortex [11] may give hints for further simplified developments. Figures 9 and 10 show results for k production due to shear in the boundary layer within the above mentined k-epsilon-model. The first case is for attached flow where a simple empirical (Michel) model was used to set the free transition point from laminar to turbulent flow.

Due to the instable wake the convective transport of k is not as effective as in the design-wind case. High areas of turbulence are closer to the blade.

In the second case - for a 30%-thick airfoil at 12 deg angle-of-attack - much more k is produced due to separation. Note that the inflow velocity is much lower than in fig. 9, so the scale of k is also reduced. Nevertheless turbulence intensity is higher than compared to the first 2D example.
Figure 10: Turbulent kinetic energy (k) within the boundary layer for a typical thick wind-turbine airfoil (FFA W3 300) where the boundary layer is separated. Angle of attack is 12 degree. Inflow velocity is somewhat lower than in fig. 9. Note that inside the recirculation zone the turbulence intensity is in the order 40%.

References

[8] D.C. Wilcox, Turbulence Modeling for CFD, DCW Industries, Inc. La Canada, California, USA, 1993