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Pena Diaz, Alfredo; Bechmann, Andreas; Conti, Davide; Angelou, Nikolas; Mann, Jakob

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The fence experiment – a first evaluation of shelter models

Alfredo Peña, Andreas Bechmann, Davide Conti, Nikolas Angelou and Jakob Mann

DTU Wind Energy, Risø campus, Technical University of Denmark, Roskilde, DK

E-mail: `aldi@dtu.dk`

Abstract. We present a preliminary evaluation of shelter models of different degrees of complexity using full-scale lidar measurements of the shelter on a vertical plane behind and orthogonal to a fence. Model results accounting for the distribution of the relative wind direction within the observed direction interval are in better agreement with the observations than those that correspond to the simulation at the center of the direction interval, particularly in the far-wake region, for six vertical levels up to two fence heights. Generally, the CFD results are in better agreement with the observations than those from two engineering-like obstacle models but the latter two follow well the behavior of the observations in the far-wake region.

1. Introduction

Our main interest in this study is to evaluate a number of shelter models that are used when performing wind-resource assessment studies. The shelter behind obstacles is particularly challenging to model as the flow characteristics can be rather complex. Wind turbines are generally sited at locations where the influence of obstacles is negligible but more turbines are being 'exposed' to obstacles due to the lack of available 'free' sites. Further, small turbines are installed close to buildings (due to regulations), thus suffering production losses and increased damage due to loading.

The fence experiment was a full-scale field experiment conducted at the test site of the Risø campus of the Technical University of Denmark (DTU). The experiment and the measurements are described in detail in ref. [1]. The result of the experiment is a comprehensive dataset of observations (namely seven benchmark cases) of the shelter on a vertical plane behind and orthogonal to a fence and of the inflow conditions that were derived from measurements of two sonic anemometers mounted on a nearby meteorological mast. The data of the benchmark cases can be found in ref. [2]. The measurements on the vertical plane were performed with the WindScanner (WS) system, which consists of three short-range temporally- and spatially-synchronized continuous-wave coherent lidars; thus the WS is capable of measuring the three velocity components by combining the measurements of the line-of-sight velocities of the three lidars. The main purpose of the experiment was to serve as a benchmark for the evaluation of flow models because full-scale shelter observations are nearly non-existent. Most studies are focused on porous obstacles ([3–5]) because the experiments are designed to optimize windbreaks for stock and crop protection. Comparison of flow model simulations of windbreaks with measurements is provided in ref. [6].

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2. Experimental setup of the fence experiment

In ref. [1], the WS and the sonic anemometer data were classified into seven cases so that the influence on the shelter of relative direction intervals, atmospheric stability, and porosity can be studied. In this first evaluation of shelter models, we will focus on case II, which corresponds to measurements using a solid fence (3 m high, 30 m wide and 0.04–0.1 m thick) with inflow conditions within an interval of relative wind directions $\theta = 0° \pm 30°$ (see Fig. 1-top right). For this case, the estimated ensemble-average surface roughness length $\langle z_o \rangle$ and dimensionless stability parameter $\langle z/L \rangle$ are 0.0019 m and 0.015, respectively ([1]), i.e. a roughness typical of smooth terrain (the influence of the fjord ≈78 m upstream of the fence is notorious; see Fig. 1–top left) and a slightly stable atmosphere.

In ref. [1], the WS measurements on the vertical plane x-z were gridded so that the final scanning pattern has 31×7 points (see Fig. 1-bottom). The seven vertical levels are always at the same height above ground, $[0.21, 0.46, 0.71, 0.96, 1.46, 1.96, 2.46]\,h$, where h is the fence height, and in ref. [2] the exact grid locations along the x-coordinate are given.

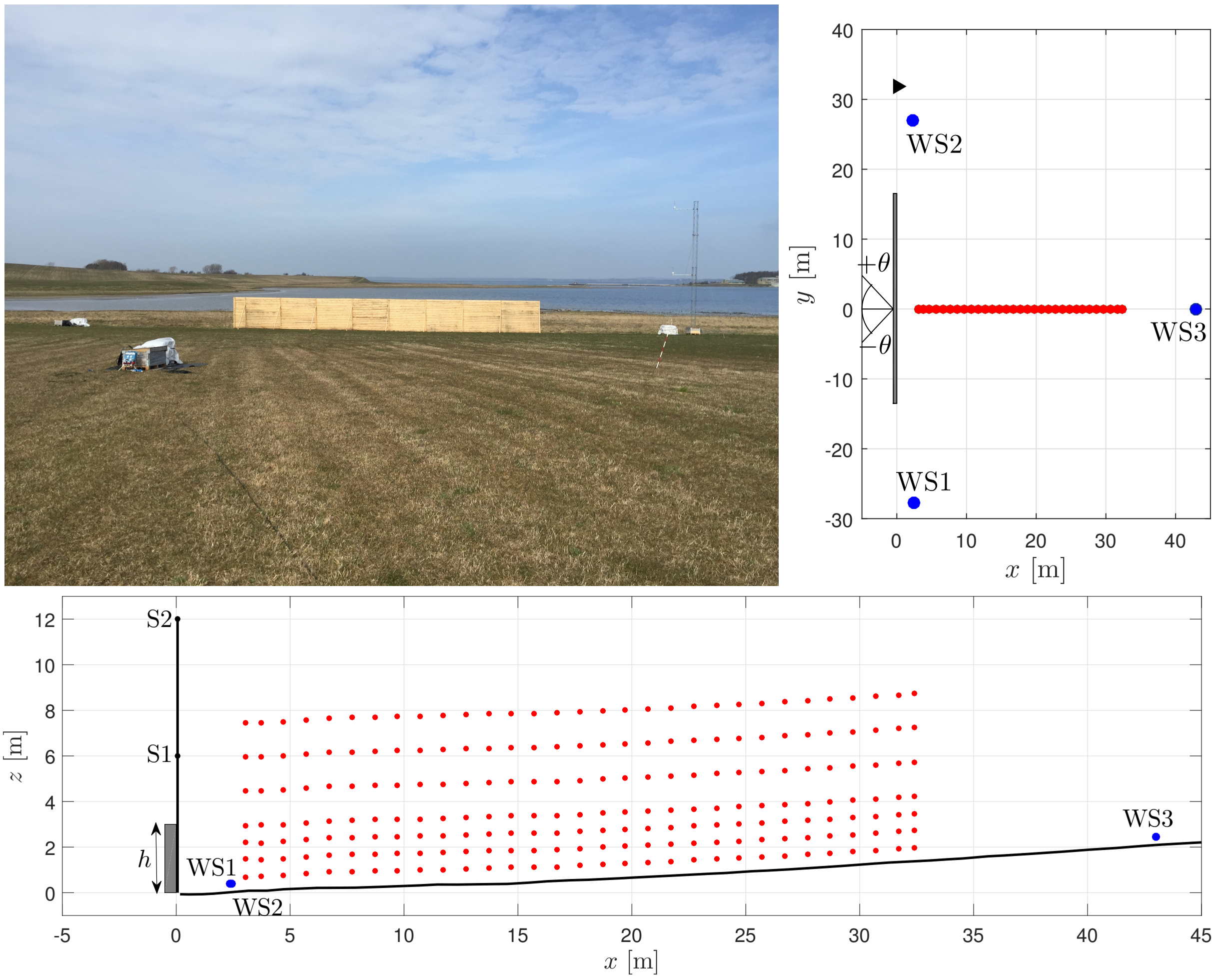

Figure 1. The fence experiment at the Risø test site (top-left frame). Schematics of the experimental setup are also shown: top (top-right frame) and side views (bottom frame). The positions of the fence of height h (gray rectangle), the WS lidars (blue circles), the mast (triangle on the top view and black thick line on the side view) with the sonics (S1 and S2), and the scanning grid (red circles) are also illustrated. The terrain elevation is shown in the black solid line in the side view

3. Methods

We evaluate three models using the shelter observations of case II; a computational fluid dynamics (CFD) model solving the Reynolds Averaged Navier-Stokes (RANS) equations (hereafter CFD), and two engineering-like obstacle models: the Wind Atlas Analysis and Application Program (WAsP) shelter model (hereafter WAsP-shelter) and WEMOD. Here we provide a short overview of the models; further details of the models can be found in ref. [7]. The coordinate system used has its origin at the bottom of the fence (x is positive downwind and perpendicular to the fence). A right-handed Cartesian coordinate system is used, where the wind speed components (u, v, w) are aligned with the axes (x, y, z) and the horizontal wind speed is defined as $U = (u^2 + v^2)^{1/2}$. The slope of the terrain is not taken into account in the models or in their results.

3.1. CFD

The CFD model uses the Ellipsys3D flow solver ([8]), which is a finite volume discretization of the RANS equations. Turbulence is modeled with a standard two-equation RANS model with constants typically used for atmospheric flow. The atmosphere is treated as neutral and Coriolis-related terms are neglected. The fence is physically modeled using the full-scale dimensions but the thickness in the model is set to 0.5 m in order to improve convergence due to the chosen CFD mesh block-topology. CFD simulations of the flow over the fence are performed for $\theta = [0, 10, 20, 30]^\circ$ with the condition $h/z_o = 300$.

3.2. WAsP-shelter

The model is based on the expression of Perera ([9]),

$$\frac{\Delta u(z)}{u_o(h)} = A\,(1-\varphi)\left(\frac{x}{h}\right)^{-1} \eta \exp\left(-0.67\eta^{1.5}\right), \tag{1}$$

where $\Delta u(z) = u_o(z) - u(z)$, i.e. the difference between the undisturbed (subscript $_o$) and sheltered value, φ is the fence porosity, A a constant (=9.75), $\eta = (z/h)\,(K\ x/h)^{-1/(n+2)}$, $K = 2\kappa^2/\ln(h/z_o)$, and κ is the von Kármán constant (=0.4). Equation (1) is a simplified version of the expression by Counihan et al. ([10]), which is based on an analytical 2D wake theory.

The power law is used to estimate the ratio $u_o(h)/u_o(z)$ with a shear exponent $n = \ln(z/z_o)^{-1}$ and so the wind speed ratio is computed as

$$\frac{u(z)}{u_o(z)} = 1 - \frac{\Delta u(z)}{u_o(h)}\,\frac{u_o(h)}{u_o(z)}. \tag{2}$$

Shelter is estimated in a sector-wise sense, and a wall layer is matched close to the surface and behaves similar to an internal boundary layer from roughness changes. The wake spreads linearly and laterally from the obstacle. The simulations are performed with an angular resolution of 1.11°.

3.3. WEMOD

The model is well described by Taylor and Salmon ([11]) and is, in principle, very similar to WAsP-shelter. However, in WEMOD the lateral spread of the wake is assumed to be Gaussian. The simulations are performed with an angular resolution of 1°.

4. Preliminary results

For each of the models, there are two types of results for the wind speed ratio (see Fig. 2). The one in dotted lines refers to the model result at the center of the interval of relative wind directions, in this particular case at $\theta = 0°$ (hereafter known as 'standard' result). The one in solid lines refers to the model result that takes into account the distribution of relative wind directions of the case (see Fig. 3), which are data extracted from ref. [2], i.e. we ensemble-average the simulated wind speed ratio for each relative wind direction, taking into account its relative weight in the total wind direction distribution. The latter will be referred to as 'non-standard' result.

Figure 2 illustrates the results for the first six vertical levels, where the fence affects the flow the most. The differences between the non-standard and the standard results increase with distance from the fence and such differences are higher for the CFD simulations than for the WEMOD and WAsP-shelter simulations. This is because although WEMOD and WAsP-shelter can take into account the relative wind direction, only the magnitude of the horizontal wind speed is modeled, whereas for the CFD simulation the wind field is entirely simulated. For the standard case, the v-component in the CFD simulation is simply zero, whereas it can have a strong influence on the horizontal wind speed magnitude as illustrated in Fig. 4, where we show the results of the CFD model for the lowest level and for $\theta = 30°$. The shelter observations show the importance of the v-component (see the right frames in Figs. 9–11 in ref. [1]). The non-standard CFD results show a 'step-like' behavior for $z/h \leq 0.71$ because of the v-component resulting from the simulations with relative directions other than zero. As illustrated in Fig. 4, the v-component can be large and positive within a region where the u-component changes sign (in this case at $x/h \approx 4$).

WEMOD and WAsP-shelter results are very similar for $z/h \geq 0.96$ and for $z/h < 0.96$ they disagree for $x/h \lessapprox 6$ due to shelter limitations that are 'artificially' imposed in WAsP-shelter. Interestingly, the non-standard CFD results approach those from WEMOD and WAsP-shelter at all vertical levels when $x/h \gtrapprox 6$, which is considered the far-wake region. Near the fence (the near-wake region), i.e. $x/h \lessapprox 4$, the CFD results agree better with the observations than the engineering-like models, whereas the results from WEMOD, in particular for the region $4 \gtrapprox x/h \gtrapprox 5$, are in better agreement with the observations. There is a peak in the wind speed ratio within the near-wake region that is not captured by the engineering-like models for $z/h \leq 0.46$, and in the near-wake region and for $z/h > 0.71$, the wind speed ratio is generally underestimated by the engineering-like models and do not follow the behavior of the observations.

5. Discussion

Interestingly, the engineering-like models overestimate the shelter in the far-wake region for $z/h \leq 1.46$, where the 2D wake theory, which serves as basis for the models, can be applied. The constant A in Eqn. (1) is the product of an integral constant and the wake moment coefficient ([10]); for the latter Perera ([9]) assumes the value 0.8 (based on 2D obstacles) and, later, Taylor and Salmon ([11]) suggest lower values (about half that of Perera) when dealing with 3D obstacles. This is the main reason why these two engineering-like models are known to be 'conservative' when used with the default parameters. When used for wind resource assessment, the predicted wind climate (PWC) will be underestimated if the obstacles are close to the wind turbine but the PWC will be overestimated if the obstacles are close to the observations (e.g. from a mast). It is important to highlight that these two engineering-like models are recommended for shelter calculations within the region where $z/h < 3$ and $x/h < 50$ but excluding the near wake region (see Fig. 2 in ref. [7]).

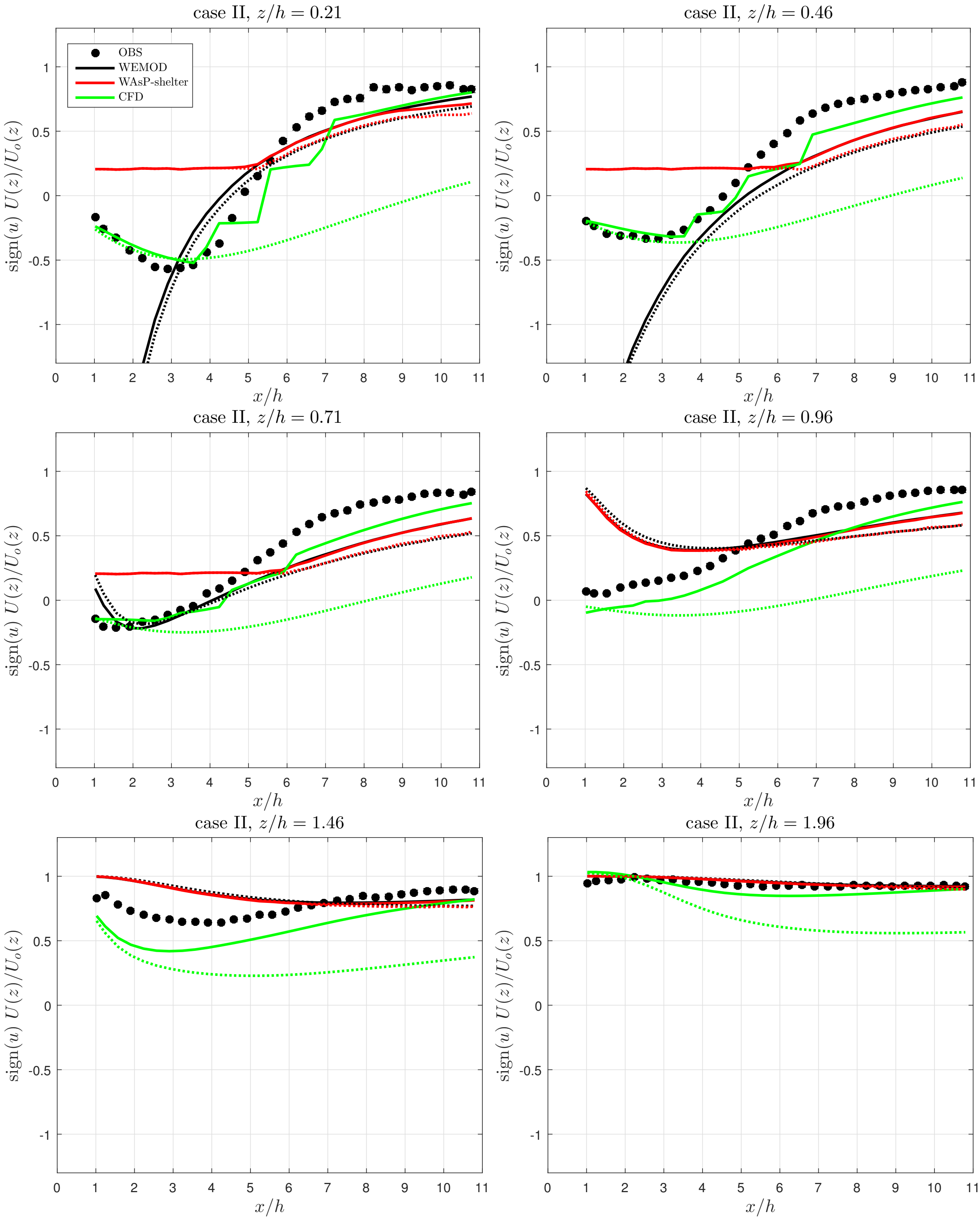

Figure 2. Wind speed ratio on the vertical plane behind and orthogonal to the fence for six vertical levels for case II of the fence experiment. OBS are the observations and results from different models are shown in different line types (see text for details)

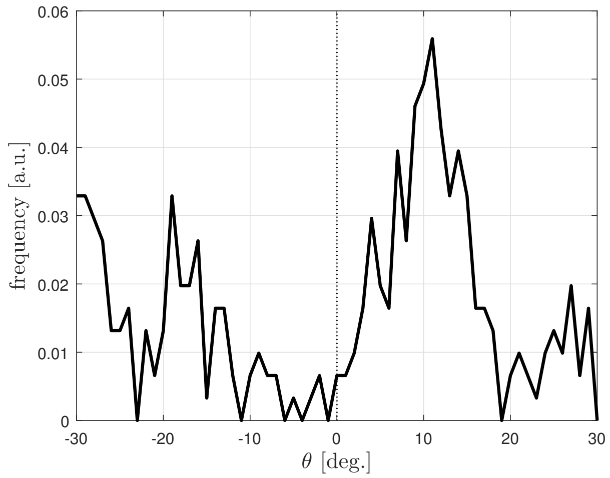

Figure 3. Frequency of relative directions for case II based on the measurements of the sonic anemometer at 6 m

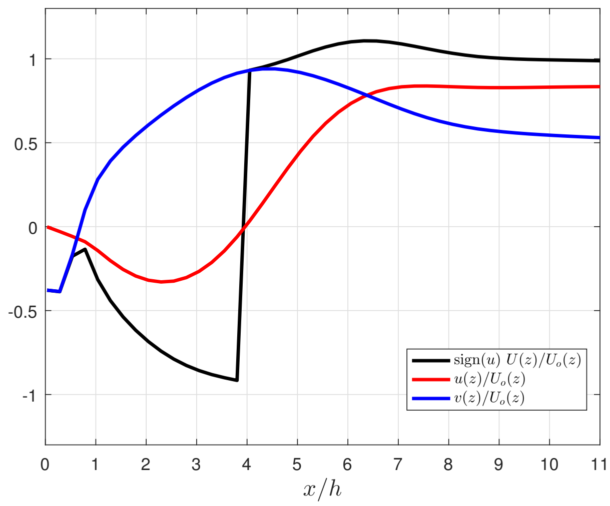

Figure 4. Wind speed ratio at $z/h = 0.21$ for the direction $\theta = 30°$ from the CFD simulation results. The three lines represent the results using either U, u, or v

6. Conclusions

The CFD results that take into account the relative wind direction distribution are generally closer to the observations of the fence experiment when compared with those from 1) the CFD simulation performed at the center of the interval of relative directions and 2) the two engineering-like models. When compared to the latter two models, the difference is highest in the near wake. The engineering-like models are in good agreement with the observations in the far wake, as expected, overpredicting the shelter of the fence for vertical levels below two fence heights.

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