Shelter models and observations

Peña, Alfredo; Bechmann, Andreas; Conti, Davide; Angelou, Nikolas; Troen, Ib

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Shelter models and observations

Alfredo Peña, Andreas Bechmann, Davide Conti, Nikolas Angelou and Ib Troen

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Shelter models and observations

Alfredo Peña, Andreas Bechmann, Davide Conti, Nikolas Angelou and Ib Troen
Abstract (max. 2000 char)

This report documents part of the work performed by work package (WP) 3 of the ‘Online WAsP’ project funded by the Danish Energy Technology and Demonstration Program (EUDP). WP3 initially identified the shortcomings of the current WAsP engine for small and medium wind turbines (Peña et al., 2014b), adapted the WAsP engine to Online WAsP (www.wasponline.dk), and made an effort to quantify the error and the uncertainty, first of the obstacle model in WAsP and later of the WAsP model chain. This report documents the work done for the obstacle model.

In addition, EUDP supports the IEA task 27 on ‘small wind turbines in high turbulence sites’, which aims at acquiring a better understanding of the wind conditions in which small turbines operate. This support helped us setting up a full-scale field experiment conducted at DTU’s test site at Riso, Roskilde, where we measured the flow characteristics in the wake of a fence. The experiment is the basis of the study of the error and uncertainty of the obstacle models.
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8 Summary and conclusions

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References
1 Introduction

The shelter behind obstacles is one of the most complex flows to measure and to model and so its study is important in applications such as wind energy. However, during the exponential-growth period of the wind industry, the shelter did not significantly represent an issue for turbine energy-yield estimation because the machines were sited in free-shelter regions. Currently, due to the less available ‘best’ wind sites, many turbines are deployed close to obstacles. Also the small wind industry has grown and in some countries, due to planning rules, small wind turbines are placed very close to houses, representing an increase of the sheltering effects.

A number of engineering-like obstacle models are based on the work of Perera (1981) (P81 hereafter), who studied the shelter behind two-dimensional solid and porous fences immersed on wind-tunnel simulated atmospheric boundary layer and suggested a simple empirical formula to estimate the shelter behind obstacles. Here, we study two models of this family, namely, the shelter model used in the Wind Atlas Analysis and Application Program (WAsP) (Mortensen et al., 2007), which we refer to as WAsP-shelter, and that developed by Taylor and Salmon (1993) (T&S93 hereafter), which we refer to as WEMOD, and compare them against shelter measurements collected from the literature. Computational fluid dynamics (CFD) simulation results are also used for the intercomparison.

In addition, we present a dataset of full-scale measurements of the shelter behind a 3-m tall and 30-m wide solid fence, which were performed at DTU’s Risø campus in Roskilde, Denmark. The measurements were conducted by the short-range WindScanner (WS) system (http://www.windscanner.dk), where three synchronized wind lidars measured the 3D wind velocity vector on a vertical-plane grid behind the fence. The measurements represent a wide variety of atmospheric conditions, and different cases are analyzed as function of the relative direction of the fence to the inflow. We evaluate both engineering- and CFD-like shelter models using this comprehensive dataset.
2 Analytical solutions of the shelter

2.1 The 2D infinite fence model of Perera (1981)

P81 suggested an empirical expression for the ratio of the velocity difference \( \Delta u(z) = u_o(z) - u(z) \), where \( u_o(z) \) and \( u(z) \) are, respectively, the undisturbed and obstacle-disturbed velocities at height \( z \) to \( u_o(h) \) (i.e., the undisturbed velocity at the obstacle height \( h \)) of an infinitely wide thin fence (a 2D fence). This can be read following the ‘convention’ of Taylor and Salmon (1993) as

\[
\frac{\Delta u(z)}{u_o(h)} = \Gamma \tilde{C}_b \left( \frac{x}{h} \right)^{-1} G(\xi),
\]

with

\[
G(\xi) = c_o \xi \exp(-a_o \xi^{1.5}),
\]

where \( c_o = \left[ \ln(h/z_o) / (2 \kappa^2) \right]^{1/(\alpha+2)} \), \( a_o = 0.67 c_o^{1.5} \), \( \xi = (z/h)(x/h)^{-1/(\alpha+2)} \), \( x \) and \( z \) the downstream and vertical distances from the obstacle, \( z_o \), the upstream roughness length, \( \tilde{C}_b \) the normalized wake moment coefficient, and \( \kappa \) the von Kármán constant (\( \approx 0.4 \)). For 2D obstacles T&S93 recommended \( \tilde{C}_b = 2 \tilde{C}_b / 3 \), where \( \tilde{C}_b \) is the normalized drag coefficient. With \( \Gamma = 12.1875 \), and \( \tilde{C}_b = 0.8(1 - \varphi) \), where \( \varphi \) is the fence’s porosity, the expression in T&S93 perfectly matches that of P81 (we will use these values/expressions for \( \Gamma \) and \( \tilde{C}_b \) unless stated otherwise). P81 originally suggested \( n = 1/7 \) but the differences from using \( n = 0 \) in Eq. (1) are negligible (here \( n = 1/7 \) is always used unless otherwise stated), \( n \) is the shear exponent of the power law, which for atmospheric neutral conditions becomes \( \approx \ln(z/z_o) \) \( -1 \).

The term \( \Delta u(z)/u_o(h) \) is not a speed-up but a normalized velocity deficit. To estimate the speed-up \( u/u_o \) at a specific height \( z \) one could use,

\[
\frac{u(z)}{u_o(z)} = 1 - \frac{\Delta u(z)}{u_o(h)} \frac{u_o(h)}{u_o(z)},
\]

and so we only need to know something about the behavior of the undisturbed vertical wind profile to compute the term \( u_o(h)/u_o(z) \). For such a purpose we can use the diabatic wind profile,

\[
\frac{u_o(h)}{u_o(z)} = \frac{\ln(h/z_o)}{\ln(z/z_o)}.
\]

Or we can use the power law,

\[
\frac{u_o(h)}{u_o(z)} = \left( \frac{h}{z} \right)^n.
\]

2.2 The WAsP obstacle model – WAsP-shelter

The description of the obstacles in WAsP-shelter is similar to that in WEMOD (see Fig. 3 in Sect. 2.3). One inputs the radial distances of the sides of the obstacle closest to the point of interest and in addition the height, porosity, and depth. In principle the model uses Eq. (1) with \( n = \ln(z/z_o) \). However, the shelter calculations are performed to suit the sector-wise analysis of WAsP. The idea behind the model is to estimate the shelter of obstacles for different directions but always from the point of view of the position of interest \( A \), so centered at this location a number of rays are simulated in a polar grid and the distances \( R_i \) of the obstacle segments cut by the rays are computed. For each of these rays:

1. if the point of interest is in the ‘immediate wake’ considered as a wedge with slope 0.2 extending downward from \( h \), then out to a distance of 5 \( h \), the shelter is considered constant
2. if the distance downstream is \( > 5 \, h \), then an equilibrium height is considered and estimated as:

\[
 z_{eq} = 0.3 \, z_o \left[ 5 (x_i - h)/z_o \right]^{0.8} + 3 \, z_o ,
\]

(7)

if \( z < z_{eq} \) then \( z_i = z_{eq} \); otherwise for \( z > z_{eq} \), \( z_i = z_{eq} \). With \( \zeta_i = (z_i/h)(x_i/h)^{-1/(n+2)} \) then

\[
 \Delta u_s(z) = 9.751 \left( 1 - \varphi \right) (x/h)^{-1} G(\min(\zeta_i, 12)),
\]

(8)

3. the speed deficit is then estimated as \( \Delta u_s(z)/u_o(h) \) \( \ln(z/z_o) / \ln(z_{eq}/z_o) \)

4. a shelter efficiency is calculated taking into account upstream sheltering elements on the same ray. A sheltering element is reduced in efficiency if it lies partly within the immediate wake from a upstream element (area under 1.). The total shelter for a given ray is then summed over the obstacles taking into account these efficiencies

5. the speed deficits are then block-averaged over 12° to mimic lateral spreading in the boundary layer. Figure 1-bottom shows the spreading of the wake in WAsP-shelter on the computed speed-up at \( z/h = 0.5 \) before the last step is performed

6. the relative sheltering per ray is finally averaged over the chosen azimuthal sectors used in WAsP (typically 12 30° sectors).

Figure 1: speed-up \( u(z)/u_o(z) \) on a horizontal plane behind a solid cube from WEMOD (top) and WAsP-shelter (bottom) at \( z/h = 0.5 \)

It is also important to note that WAsP-shelter is traditionally recommended for shelter calculations in WAsP when both conditions \( z/h < 3 \) and \( x/h < 50 \) are simultaneously fulfilled. WAsP also recommends to avoid its use when both conditions \( z/h < 0.5 \) and \( x/h < 10 \) are simultaneously fulfilled and also when both conditions \( z/h < 3 \) and \( x/h < 5 \) are simultaneously fulfilled. These recommendations are summarized in Fig. 2, where we also show the shelter (in percentage) behind a near-to-infinite solid fence based on WAsP-shelter.

2.3 The model of Taylor and Salmon (1993) – WEMOD

In WEMOD the obstacle is considered to be composed of \( i \)th barrier segments of height \( h \) normal to the wind with wind direction \( \varphi \), as indicated in Fig. 3. \( \beta_i \) represents the angle from the north between each segment and the location \( A \) where we want to estimate the shelter, which is at

\[
 z_{eq} = \ldots
\]
Figure 2: WASP recommended (green) and not recommended (red) regions for the use of WASP-shelter. Contours indicate the shelter 1 − u(z)/uo(z) in percentage of an infinite solid fence simulated with WASP-shelter for h/zo = 100.

the position (0,0). With an angular resolution Δβ, βi will take values within the range \([αL + Δβ/2^\circ, αR − Δβ/2^\circ]\) with Δβ° increments, being αL and αR the two angles from north of the two most extreme left \((x_L, y_L)\) and right \((x_R, y_R)\) positions of the obstacle, respectively, with respect to A. The distance between A to the center of the barrier i is given as

\[
R_i = \frac{x_{RY}L - x_{LY}R}{(x_R - x_L)\cos β_i - (y_R - y_L)\sin β_i}. \tag{9}
\]

Figure 3: Obstacle representation in WEMOD (see text for details)

The angle made by the normal to the line between the two most extreme obstacle positions can be estimated as \(\tan γ = (y_L - y_R)/(x_R - x_L)\). The width of the segment i can be approximated to

\[
w_i = 2R_i\sin(Δβ/2)\sec(β_i - γ)|\cos(ψ - γ)|. \tag{10}
\]

In a second Cartesian frame of reference with coordinates \((x, y)\) located at the center of each segment i with the x-axis aligned with the flow, the location of A with respect to each segment i will then be at \((xi, yi) = [R_i\cos(ψ − β_i), R_i\sin(ψ − β_i)]\). The velocity reduction of an upwind
segment $i$ of an obstacle $s$ can then be computed as

$$\frac{\Delta u_{s,i}(z)}{u_o(h)} = \Gamma \bar{C}_h \left( \frac{w_i}{h} \right) \left( \frac{x_i}{h} \right)^{-1.5} G(\xi_i) F(\lambda_i),$$

(11)

with

$$F(\lambda_i) = \frac{1}{\sqrt{2\pi a_f}} \exp \left( -\frac{\lambda_i^2}{2a_f^2} \right),$$

(12)

where T&S93 recommended $a_f = 0.5$, $\lambda_i = (y_i/h)(x_i/h)^{-1/2}$, and $\xi_i = (z/h)(x_i/h)^{-1/(n+2)}$. $F(\lambda_i)$ represents the lateral spread of the wake, which, as shown from Eq. (12), is assumed to be Gaussian.

The overall effect of an obstacle $s$ is given by the summation of the effects of all segments $i$. T&S93 provide a discussion on how to account for the effect of multiple obstacles, which is not needed here as we will focus on the effect of a single obstacle only. Figure 1-top shows the Gaussian effect of the lateral spread of the wake of the WEMOD model on the computed speed-up at $z/h = 0.5$. 


3 RANS-CFD

3.1 The CFD model

For all computational fluid dynamics (CFD) simulations performed in this report we use the EllipSys3D code (Sørensen, 2003), which is a general-purpose flow solver originally developed to solve the flow characteristics over hills. The EllipSys3D code is a multiblock finite volume discretization of the incompressible Reynolds Averaged Navier-Stokes (RANS) equations in general curvilinear coordinates. The convective terms are discretized using a third order QUICK upwind scheme, implemented using the deferred correction approach first suggested by Koshla and Rubin (1974). Central differences are used for the remaining terms. It is parallelized with MPI for execution on distributed memory machines, using a non-overlapping domain decomposition technique and is further accelerated, using a multi-level grid sequence in steady state computations. The numerical solution of the CFD simulations is only stopped when all variable residuals are below $5 \times 10^{-5}$. Turbulence is modeled using the two-equation $k-\varepsilon$ RANS model by Launder and Spalding (1974). Fixed model constants calibrated for atmospheric flows are used.

3.2 Inflow conditions

For the flow cases considered, the atmosphere is treated as neutrally stratified and Coriolis forcing is neglected; thus the flow is Reynolds-number independent. The CFD results are therefore only dependent on the inflow direction and on the inflow profiles that are specified as function of the upstream surface roughness. The logarithmic equilibrium profiles for the horizontal wind speed, i.e., Eq. (4) with $\psi_m = 0$, and turbulent kinetic energy $k$, are used for the inflow and wall boundary conditions,

$$k = u_*^2/C_{\mu}^{1/2},$$

where $C_{\mu} = 0.052$. Since EllipSys3D is a fully dynamical model, both the highly disturbed flow situations including flow separation and form drag of the fence are modeled.

3.3 The computational grid

Three different CFD grids have been used in this report; for simulation of the 3D fence, for the cube simulations and for the 2D infinite fence.

3.3.1 3D fence

The width and height of the computational domain is chosen as a balance between minimizing the blockage effect of the obstacles and the computational resources used. The domain has a height of 60 m, width of 300 m and length of 400 m. The fence has a height of 3 m and width of 30 m. The ratio between the frontal area of the fence and the cross-sectional area of the domain is 0.5 % indicating that blockage from the domain boundaries has little influence. The fence is placed 40 m from the inlet; providing a long (360 m) downstream fetch for the wake to recover before reaching the outlet of the domain - this helps convergence of the simulations. In order to be able to run different wind directions, the domain has outlet conditions (Neumann boundary conditions) at two horizontal planes and inlet conditions at the others (see Fig. 4). Inlet conditions were also used at the top of the domain.

The domain is divided into 1494 blocks each of $16^3$ cells. The domain has a length of 12 blocks in the $x$-direction, a width of 12 blocks in the $y$-direction and a height of 10 blocks. Since no mesh block is needed at the obstacle location a total of 1494 blocks or 6.1 million cells are used.

A rectangular grid stretched towards the walls was used for the fence simulations. In order to capture the high velocity gradients the near-wall grid cells are only 0.03 m tall and coarsen with distance to the wall. Downstream of the fence the vertical grid resolution is kept in order
Figure 4: (Left) red is inlet condition, blue outlet conditions, rough wall boundary conditions. (Right) the block structure to accurately model the development of the fence wake (see Fig. 5). Due to the mesh topology the fence has a thickness of 0.5 m. This was done to get a gradual coarsening of the grid cells necessary to achieve fast convergence of the CFD simulations. The coordinate system used has origin at the bottom downstream edge of the fence. The same roughness values for the ground walls are used for the obstacles’ surfaces.

Figure 5: Computational grid from the top (top left) and a close up (top right), and from the side (bottom left) and a close up (bottom right) of a modeled fence. Similar computational grids are used for modeling the other type of obstacles

To ensure that the computational grid has adequate resolution to resolve the flow, a grid dependency study has been performed. By removing every second grid point in all directions a coarse grid has been made (grid level 2), and by repeating an even coarser grid has been made (grid level 3). Results from each of the 3 computational grids give near identical results (not shown) and it can be concluded that the generated grid has adequate resolution to resolve the flow.

3.3.2 The cube

The computational domain used for the cube simulations are similar to the one used for the 3D fence simulations. The domain also has a height and width of 60 m and a length of 250 m. The cube has a height of 3 m giving a ratio between the frontal areal and the cross-sectional area of the domain of 0.25 % indicating that blockage from the domain boundaries has little influence. The cube is placed 50 m from the inlet; providing a long downstream fetch for the wake to recover before reaching the outlet of the domain. In order to be able to run different wind directions, the domain has cyclic conditions at two horizontal planes. 2.9 million grid cells were enough to accurately capture the flow. Similar to the 3D fence grid,
a rectangular grid stretched towards the walls was used. In order to capture the high velocity gradients the near-wall grid cells are only 0.05 m tall and coarsen with distance to the wall. Downstream of the cube the vertical grid resolution is kept in order to accurately model the development of the fence wake (see Fig. 6). The coordinate system used has origin at the bottom downstream edge of the cube and the same roughness values for the ground walls are used for the obstacles' surfaces.

![Figure 6: The computational grid of the cube mesh. The cube has been colored for visualization purposes](image)

### 3.3.3 2D infinite fence

The 2D infinite fence grid is almost identical to the 3D fence grid. The difference is that the width of the domain has been decreased to 30 m and that the boundary conditions for the two transverse vertical planes has been set to symmetry. This has been done in order to use the 3D solver to solve this 2D problem.
4 Comparison of analytical models with CFD results and (some) shelter measurements

Here we present intercomparisons of the shelter results from simulations using the models presented in Sects. 2 and 3. This is performed for cases commonly found in the literature, in which some measurements are also available.

4.1 2D infinite solid fence

Figure 7 illustrates the speed-up simulated on a vertical plane downstream an infinite 2D thin fence with \( h/z_o = 100 \), which is similar to the value for a small house over a semi-urban area. By using Eq. (1) (top left frame), the estimated speed-up is always positive within the ranges \( z/h > 1 \) and \( x/h > 5 \) and outside these ranges, i.e. very close to the obstacle, it becomes negative with values largely increasing in magnitude the closer the distance to the obstacle.

Figure 7-bottom left illustrates the results using WEMOD (the dimensions used for the simulation are \([\Delta x, \Delta y, \Delta z] = [0.1, 2000, 1] \) m) with \( \Delta \beta = 0.1^\circ \). As illustrated the results are nearly identical to those using Eq. (1) because, as mentioned by T&S93, the summation of the formulas for 3D component barriers recovers P81’s original formulation. Figure 7-bottom right illustrates the WASP-shelter simulated speed-up (same dimensions as those used for WEMOD). It is noticed that the deficit due to the obstacle is limited due to the equilibrium layer and close to the obstacle, where Perera’s results are negative (and thus out of the colorscale).

Figure 7-top right illustrates the result for the CFD computations. The result is qualitatively
the most different compared to the other three but perhaps the most ‘realistic’ as we neither limit
the shelter results nor the colorscale in the figure, which means that the magnitude of the reverse
flow close to both the obstacle and the ground might be close to what we will observe.

4.2 2D infinite porous fence

4.2.1 Slightly porous fence

Following T&S93 we compare results from WEMOD with some of the results of P81’s wind
tunnel cases ($h/z_o=100$ and $z/h = 0.5$ m) and we extend the comparison with the results of
WAsP-shelter to two more heights. The downstream variation of the speed-up behind a slightly
porous fence ($\varphi = 0.1$) is illustrated in Fig. 8.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Speed-up downstream an infinite 2D porous fence. Solid lines are simulations using
WEMOD and dashed lines using WAsP-shelter (for these two models the fence is 2000 m long,
1 m tall, and 0.1 m deep). Observations from P81 for the $z = h/2$ case are also shown in filled
squares.}
\end{figure}

The results from WAsP-shelter are very close to those using WEMOD. Far downstream there
is a slight difference between WAsP-shelter and WEMOD for $z = h/2$ ($x/h > 10$) and it is noticed
the speed-up limitation imposed in WAsP-shelter close to the obstacle (min($u(z)/u_o(z)$) $\approx 0.3$).
P81 showed measurements for different types of fences for the $z = h/2$ case (here only one type
is shown) and the agreement with WAsP-shelter and WEMOD is very good within the range
$x/h > 5$.

4.2.2 Porous fence

T&S93 also compared the reduction with height behind a similar but slightly more porous fence
also shown in P81 (P81 has measurements for the solid fence as well). Results from WEMOD,
WAsP-shelter and CFD simulations are illustrated in Fig. 9. The axes are normalized to derive
the self-similar profiles as in P81: $\bar{u} = [\Delta u(z)/u_o(h)] (x/h)$ and $\eta = c_a \zeta$. With such normalization
the variation of $\bar{u}$ as function of $\eta$ in Eq. (1) is the same for all downstream distances.

Results from WEMOD show the self-similarity of these profiles, i.e. all results are on top of
each other as expected, whereas those from WAsP-shelter show the limits imposed to the speed-
ups, which are already noticed at $x/h = 5$. Results using WEMOD are in good agreement with
the measurements in P81 for the case $x/h = 25$, as expected, as the WEMOD results for this
case are equal to those from Eq. (21), which was fit by Perera (1981) to the measurements. CFD
Figure 9: Self-similar velocity profiles behind and infinite 2D porous fence. Solid lines are simulation results using WEMOD and dashed lines using WASP-shelter both models using the same geometry as in Fig. 8. Dash-dotted lines are CFD simulation results. Observations from P81 for the case $x/h = 25$ are also shown in markers results show in some degree the self-similarity of the profiles, although very close to the obstacle the values are also ‘limited’ in a similar fashion to those from WASP-shelter.

4.2.3 WASP-recommended region for a solid fence

The last 2D-like comparison performed by T&S93 is related to the sheltering caused by an infinite 5-m high solid fence located 100 m north from an anemometer location ($z_o = 0.03$ m) for three heights 5, 10, and 20 m and for a range of wind directions (see Fig. 10). Only model simulation results are available but the case is interesting as the shelter is computed within regions where we use shelter models for wind resource assessment.

The agreement between simulation results using WEMOD and WASP-shelter is very good but this is mainly because we are dealing with shelter in the far field ($x/h = 20$). The highest differences are found the more parallel the flow gets compared to the fence’s longest side, i.e. close to 90°, due to the way of accounting for the 3D effects in the models. However, the shelter for such directions is anyway very small.

4.3 The ‘ideal’ cube

Figure 11 shows the simulated speed-up on a vertical plane downstream a cube and, as expected, the speed deficits are concentrated within a region closer to the cube compared to the results of the infinite fence. It is important to notice that T&S93 recommended the use of a lower $\tilde{C}_h$ for 3D obstacles, which dramatically changes these results (the region with reduced speed-ups is largely decreased). Compared to the CFD results a much lower $\tilde{C}_h$ seems to result in large underprediction of the shelter for the engineering-like models.

4.4 The cube of Lemberg (1973)

T&S also showed a comparison for the 3D sheltering effect, namely with the wind-tunnel case study of Lemberg (1973) (L73). These measurements correspond to the wake behind a cube with 4 in sides. Figures 12 and 13 illustrate the results of the WEMOD, WASP-shelter and CFD models for L73’s cube for downstream distances at a number of vertical levels and for at cross-distances
at a number of downstream distances. T&S93 did not mention the value of $z_o$, neither L73, so it is here qualitatively adjusted to match T&S93’s results. As suggested by T&S93, we also show results using $\tilde{C}_h = 0.35$.

As illustrated the simulation results using the WASP-shelter model are close to those using WEMOD for the highest $\tilde{C}_h$ value, as expected, and larger than those of WEMOD using $\tilde{C}_h = 0.35$, which agree with the measurements from L73. T&S93 therefore suggested to include a porosity of 0.5 when using WASP-shelter for 3D obstacles (although not shown we find good agreement with WASP-shelter when using a higher porosity). Suggestions related to how to account for $\tilde{C}_h$ for different obstacle types are given in T&S93. The direction in Fig. 13 is not the wind direction but the angle between the line from the obstacle base to the cross-distance and the center line. The CFD results are generally close to those of WEMOD using $\tilde{C}_h = 0.8$ instead of 0.35, the latter the value recommended by T&S93 for flow over a cube. The comparison between the models’ results and the measurements from C&R77 were extracted from Fig. 6 in T&S93 and we assume that what they call ‘speed reduction factor’ is what we call velocity reduction, i.e., $1 - u(z)/u_o(z)$.

### 4.5 The cube of Castro and Robins (1977)

Another set of wind-tunnel measurements of the flow around a cube are those of Castro and Robins (1977) (C&R77). It is a 20-cm cube and here we will use the condition $h/z_o = 1/0.04$ instead of $h/z_o = 1/0.02$ as the upstream vertical wind profile seems to agree better with C&R77’s measurements with the rougher surface conditions; from CFD results and from those obtained using either WEMOD or WASP-shelter the differences in terms of speed-up are negligible. All the computations performed with WEMOD use $\tilde{C}_h = 0.8$ instead of 0.35, the latter the value recommended by T&S93 for flow over a cube. The comparison between the models’ results and the measurements from C&R77 is performed in terms of the ‘relative speed-up’, namely the term $u(z)/u_o(z)$. This is because the wind speed measurements in C&R77 are normalized by an undisturbed reference wind speed at the position $z/h = 10$. Thus we assume the power law, i.e., Eq. (6), to estimate the reference wind speed at this vertical level with $n = 1/4$ as suggested in C&R77.

The first qualitative comparison is illustrated in Fig. 14, where the relative speed-up is shown as function of downstream distances and aspect ratio (AR) values, i.e. cubes with different ‘depths’, thereby altering the aspect ratio and hence the flow characteristics around the cube.
Figure 11: Speed-up on a vertical plane downstream a cube. Results from WEMOD and WAsP-shelter are shown in the top left and right frames, respectively, and those from CFD in the bottom frame.

for a height half the obstacle height. There is a good agreement between the results from WAsP-shelter and WEMOD but the agreement is not as good as for the infinite 2D fence case when we get closer to the obstacle as the 3D effects become more notorious. The results when changing the AR are the same for WEMOD and WAsP-shelter but here we use a variant of the downstream distance taking into account the AR (see the x-axis of the figure). WAsP-shelter clearly sets a minimum speed-up of 0.2 for $x/h < 2$ and it is precisely in this region where the measurements from C&R77 lie.

Figure 15 shows the vertical variation of relative speed-ups at different downstream distances. The limits in WAsP-shelter are also clear as well as the under- or overestimation of the relative speed-up of WEMOD compared to WAsP-shelter and the measurements; for $x/h = 0.5$ and $z/h \lesssim 1$ WEMOD overestimates the relative speed-up, whereas it underestimates it for $1 \lesssim z/h \lesssim 1.5$. Generally, the WAsP-shelter results are closer to the measurements but this is only due to the shelter limits in the model.

The spanwise relative speed-up (at half the obstacle height) at two downstream distances is illustrated in Fig. 16. There is fairly good agreement between the WEMOD and WAsP-shelter results close to the center line ($y/h \approx 0$) and the differences when treating the 3D effects in both models are clearly observed and follow the behavior in Fig. 1. WAsP-shelter, compared to the measurements, underestimate the relative speed-up at $x/h = 0.25$ and better agreement is found at $x/h = 2.5$. WEMOD overestimates the relative speed-up close to the center line and the opposite trend is found the further from the center line for both downstream distances. Compared to the measurements WEMOD shows larger differences than WAsP-shelter but follow the Gaussian trend of the measurements.
Figure 12: Velocity reduction downstream a cube. Solid lines are results from WEMOD ($\tilde{C}_h = 0.80$), dotted WEMOD ($\tilde{C}_h = 0.35$), dashed WASP-shelter and dash-dotted CFD. Observations from L73 are shown in markers.

Figure 13: Velocity reduction as function of the angle between the line from the obstacle base to the cross-distance and the center line. Solid lines are results from WEMOD ($\tilde{C}_h = 0.80$), dotted WEMOD ($\tilde{C}_h = 0.35$), and dashed WASP-shelter. Observations from L73 are shown in markers.
Figure 14: Speed-up downstream a cube with different aspect ratios (ARs). Solid lines are WE-MOD and dashed lines WASP-shelter. Observations from C&R77 are shown in markers.

Figure 15: Variation of the speed-up with height for flow downstream a cube at different downstream distances. Solid lines are WEMOD, dashed lines WASP-shelter. Observations from C&R77 are shown in markers.
Figure 16: Spanwise variation of the speed-up of the flow downstream a cube. Solid lines are WEMOD and dashed lines WAsP-shelter results. Observations from C&R77 are shown in markers.
5 Variability in shelter models’ results

In order to find out the sources of uncertainty in the shelter models, we can at first try to analyze the major contributors to variations in the models’ outputs. Based on the parameters of Perera’s formulation, Eq. (1), the speed-up due to obstacles is wind-speed independent and assuming that the values for parameters such as $\Gamma$ and $\tilde{C}_h$ are constant, the other model parameter, which is inherently uncertain, is the roughness length. The analytical shelter models’ results and those from CFD are rather insensitive to roughness length variations (see Fig. 17). For WEMOD we also perform a sensitivity study on the effect of the resolution on the speed-up and for the case analyzed only small differences are encountered.

![Figure 17: Sensitivity of the simulated speed-up of the flow downstream a cube to roughness and angular resolution. Solid lines are WEMOD, dashed lines WASP-shelter, and dash-dotted CFD results. WEMOD results shown in black, green and blue are for angular resolutions of 0.01, 0.1, and 1°, respectively.](image)

There is one parameter however that is uncertain and inherently variable, that can have a strong effect on the model results, and that needs to be taken into account when comparing model results to measurements: the wind direction. When evaluating models (of nearly any type) with measurements (of nearly any type), particularly in the field of wind-power meteorology, the measurements are stored as time averages over periods of e.g., 10- or 30-min. But measurements normally are from ‘any’ wind direction and so for evaluating a model one normally selects a direction interval (bin) and ensemble-averages the time averages which are within this direction interval.

In many cases (perhaps most of them) the datasets provide only these ensemble averages and there is a description of the direction interval (generally the size only) in which these averages were performed (this is mainly due to easy handling of datasets). In these situations, the results of the evaluation of the models are difficult to interpret because 1) as wind-power-like observations can be difficult to make, the amount of time averages, which are normally averaged over direction intervals, is not that high and so 2) large direction intervals are then used. The problem is that the distribution of wind directions over such direction intervals does not necessarily concentrate at the center of the interval but this is the common assumption made when evaluating models with such type of datasets, particularly very complex models, as it is computationally expensive to run them for a large number of conditions (in this case wind directions). The ensemble-average observation does not necessarily reflect what the result will be if the directions within the direction interval were concentrated at the center or were uniformly distributed. Models are anyway many times...
run for the direction in the center of such an interval.

For evaluation of shelter models, we need at least to have an idea of the distribution of wind direction over such intervals or in case we have access to the time averages, we can perform model evaluation by simulating each time average. To show how important it is to simulate ‘each’ condition, we have artificially constructed distributions of the relative direction of the flow upstream a cube (0° is the direction normal to the cube side) and we have estimated the speed-up downstream the cube at $z/h = 0.5$. Figure 18 shows these distributions for a direction interval of ±10° (which can easily be the size used for ensemble-averaging the time averages); one showing measurements biased to the left of the interval, an uniform one and the center of the interval.

![Figure 18: Probability distribution function (PDF) of the relative direction within a ±10° interval](image)

Figure 19 illustrates the average speed-up simulated by WEMOD, WAxP-shelter and the CFD model assuming the direction is distributed as in Fig. 18. For all models, the differences between the results assuming an uniform and a biased distribution are rather small. However, the differences between the results assuming any distribution and that when the model is only run for the
center of the interval are much larger. For the CFD model, particularly the latter differences increase downstream the cube; the result for the center of the interval shows lower speed-up values because the other two results take into account directions not parallel to the downstream axis.

Sometimes, it is impossible to get an idea of the distribution of the time averages within e.g. a direction interval but the results in Fig. 19 show that we could at least try to simulate more than one condition or assume an uniform distribution to improve the evaluation of models. So far we have assumed that within the e.g. 10 or 30-min (the turbulent scale) the wind direction is uniformly distributed. But it is precisely within these scales that distributions are not uniform.

The effect of the ‘turbulent’ wind direction variability on model results (particularly on those from wind-turbine wake models) has already been investigated by Gaumond et al. (2014) and Peña et al. (2013, 2014a) and Peña and Réthoré (2014). Those studies show that accounting for the turbulent direction variability generally results in lower speed deficits but a higher relative area where the flow is wake-affected. Figure 20 shows an example of the turbulent variability of the wind direction within a 10-min period from sonic anemometer observations performed at the meteorological mast of Høvsøre (Peña et al., 2015) at a height of 10 m. The plot shows only one of the 358 time series that are found when filtering the Høvsøre data so that the atmospheric conditions are close to neutral and the wind speeds are within the range 4–5 m s\(^{-1}\) that is close to the values in which obstacle-disturbed wind turbines operate.

![Figure 20: Normalized probability distribution (NPD) of the relative direction observed at Høvsøre within a 10-min period. The observations are shown in the histogram with the gray bars, the normal distribution with a solid black line and with dashed lines the ±σ values (8.97°)](image)

From the figure one can see the Gaussian behavior of the wind speed variations, which is a result of the random behavior of the wind direction within these time scales. From the analysis of a number of observations, we have found that the direction within such time periods generally follow such Gaussian shape. In this particular 10-min case the standard deviation is about 9° and this is not one ‘extreme’ case as the median of the standard deviations of the 358 10-min time series is \(\approx 7°\). This means that when accounting for such variability, i.e. by trying to simulate not only one direction but all those within a 10-min period, the result of the shelter model will be normally different compared to that of a ‘single’ simulation (e.g. of the mean direction within the 10-min, which is what one traditionally does) in a somehow similar way to that illustrated in Fig. 19.

Figure 21 shows the average speed-up simulated by WEMOD at three different vertical levels downstream a cube. In this case we show two types of results; the solid lines show the speed-up when the simulation is performed for the mean direction within the time period (in this case 0°) and the dashed lines the result taking into account that the direction is Gaussian-distributed.
within the time period with a standard deviation of $\approx 7^\circ$. As expected, the speed-up assuming a direction distribution is equal or higher than that for the single simulation for the mean wind direction. The effect of the direction distribution on the speed-up tends to decrease with distance from the ground.

![Diagram](image)

*Figure 21: Average speed-up simulated by WEMOD at three vertical levels (see text for details about the different line types)*

Figure 22 shows the average speed-up simulated by WEMOD and WAsP shelter for a particular position in the vertical plane downstream the fence for different inflow wind directions. The result $\sigma = 0^\circ$ corresponds to simulations for each mean relative direction (e.g. the time average values) and $\sigma = 7^\circ$ takes into account a Gaussian distribution (with such a standard deviation) around each mean relative direction. It is clearly noticed that by assuming that within the direction interval, where each mean relative direction is found, the direction is Gaussian distributed, the shape of the speed-up as function of the mean relative direction becomes Gaussian-shaped. This is not that surprising but it is an important result because the speed-ups can be strongly influenced by the shape and extension of the distribution within the turbulent scales as well.

In summary, there are two types of direction variability. The first has to do with the distribution of time averages (e.g. 10 or 30-min) of wind directions within a given direction interval. The second has to do with the distribution of directions within the time period, from which time averages of wind direction are computed. None of the two is normally taken into account when performing evaluation of models with datasets and they should be considered as they might strongly influence model results.
Figure 22: Average speed-up simulated by WEMOD (solid lines) and WAsP-shelter (dashed lines) as a function of the mean relative direction (see text for more details about the simulations)
6 The Fence experiment

In this section, we present a shelter experiment which was performed with the objective to evaluate obstacle models and to estimate their error (and in the best scenario their uncertainty) by using a unique and comprehensive dataset of measurements behind a fence. The experimental work is documented in the manuscript entitled ‘The fence experiment – full-scale lidar-based observations of the shelter for evaluation of flow models’ by Peña et al. (2015), which is being prepared for submission to the Wind Energy journal. Here we provide a preliminary draft version of it. The notation in this section might differ slightly from the others as it is chosen to fit the structure of a journal paper.

Abstract

We present shelter measurements of a fence from a field experiment conducted at Risø, Denmark. The observations are useful for the evaluation of flow models, as comprehensive full-scale shelter datasets are rare. The measurements were performed with three synchronized lidars scanning on a vertical plane downwind of the fence. The inflow conditions are estimated based on observations from two sonic anemometers at a nearby mast, and for fence-undisturbed conditions, the lidars’ measurements agree well with those from the sonics. Topographic effects at the scanned vertical plane are negligible and at the mast position, the average inflow conditions for all cases are well described by the logarithmic wind profile. Seven cases are defined based on the relative wind direction to the fence, the fence properties, and the inflow conditions. The larger the relative wind direction, the lower is the observed shelter effect. However, consideration of the direction distribution within the direction intervals is needed when evaluating models, as this is far from uniform. For the case with the largest relative directions, no shelter from the fence is observed in the far wake (distances ≥6 fence heights downwind of the fence). When comparing a near-neutral to a stable case within the same direction interval, a stronger shelter effect is noticed. The shelter is highest below ≈1.46 fence heights and, for some cases, it can be observed at all downwind positions (extending up to 11 fence heights). Below the fence height, the porous fence has a lower impact on the flow close to the fence compared to the solid fence. Velocity profiles in the far wake converge onto each other using the self-preserving forms from two-dimensional wake analysis.

fence, full-scale measurements, lidar, obstacles, shelter, speed-up, wake

Nomenclature

- $\Gamma$ Gamma function
- $\Delta a$ difference between the undisturbed and disturbed value of a variable $a$
- $\eta$ dimensionless length scale related to the depth of the mixing region
- $\theta$ relative direction of winds towards the fence
- $\Theta_v$ virtual potential temperature
- $\kappa$ von Kármán constant ($\approx 0.4$)
- $\Lambda$ constant (=12.19)
- $\nu_t$ eddy viscosity
- $\phi$ fence/obstacle porosity
- $\psi_m$ extension to the logarithmic wind profile to account for atmospheric stability conditions
- $a_0$ inflow/undisturbed value of a variable $a$
- $a'$ fluctuations of a variable $a$ around its time average
- $\bar{a}$ time average of a variable $a$ within a 10-min period
- $\bar{a}$ time average of a variable $a$ within a WS system full-scan period
- $\bar{\bar{a}}$ time average of a variable $a$ within the period the WS system scans a grid position on the vertical plane
6.1 Introduction

The flow around obstacles, such as buildings, trees, fences, etc., is difficult to be observed and modeled mainly because of the ‘extreme’ characteristics of the turbulence and velocity shears. In wind energy, interestingly, such type of flow has not received much attention. This might be due to the urge to decrease the cost of energy, which has narrowed the research on flow characteristics to large-turbine operating conditions. These turbines generally operate in areas and at heights where the effect of obstacles can be neglected. However, in recent years due to the decrease of available ‘high wind’ sites on land, turbines are being deployed in environments where obstacles can strongly influence the local flow. In addition, the ‘small wind’ turbine industry has steadily grown Gsänger and Pitteloud (2014) and small machines are commonly installed close to buildings and houses. Due to the shelter from these structures, such installations often result in lower-than-expected energy yields and sometimes in turbine breakdown.

Advanced computational fluid dynamics (CFD) methods, e.g. those solving the Reynolds-averaged Navier-Stokes (RANS) equations or large eddy simulation, can provide accurate descriptions of the flow around obstacles and are used to study specific flow conditions Iaccarino et al. (2003); Shah and Ferziger (1997). However, they are often too computationally expensive to be implemented in wind resource assessment tools, e.g. for the estimation of annual energy production of turbines. For such a purpose, the effect of the obstacles on the local wind climate is normally estimated using engineering-like shelter models. A number of them, e.g. WEMOD Taylor and Salmon (1993) and WAsP-shelter Mortensen et al. (2007), are based on the the analytical theory by Counihan et al. Counihan et al. (1974), which describes the wake behind two-dimensional (2D) obstacles.

Analytical theories, as well as results from CFD simulations, have mainly been evaluated with
data from wind-tunnel studies Lemberg (1973); Castro and Robins (1977). However, few comprehensive full-scale three-dimensional (3D) shelter experiments have been performed. Nägeli Nägeli (1953) is, to our knowledge, the first to investigate the mean velocity profiles up- and down-wind porous windbreaks, although his data have not the adequate quality for model evaluation Seginer (1972). Most of the shelter experiments are associated with agro-engineering studies, where the purpose is the optimization of windbreaks for stock and crop protection, and are generally focused on porous obstacles Wilson (1987); Nord (1991). More recently, Brunskill and Lubitz Brunskill and Lubitz (2012) describe a field experiment where they measured the effect on the flow of walls (of different widths) and a box trailer; the data are nonetheless not presented, only the error resulting from the evaluation of a neural-network shelter model.

Here, we present a comprehensive dataset of full-scale measurements of the shelter behind a fence. The measurements were conducted at DTU’s wind-turbine test site at Rissø, Denmark and the short-range WindScanner (WS) lidar-based system (www.windscanner.dk) was used to measure the 3D wind vector at a number of positions on a vertical plane. The main objective of the experiment is to serve as a benchmark for shelter models, in particular for those used in wind resource assessment. Section 6.2 introduces the notation, definitions and the theory that we use to analyze the measurements. Section 6.3 provides details of the site and the measurements, Sect. 6.4 describes the way data are analyzed, and Sect. 6.5 presents the shelter results for a number of inflow conditions (cases). Finally, Sect. 6.6 provides some discussion and conclusions about the measurement campaign and future model evaluation.

6.2 Definitions and theory

6.2.1 The problem

We want to describe the turbulent flow behind a 2D fence, as illustrated in Fig. 23, and compare it to the undisturbed upstream flow (the inflow wind) here denoted with the subscript o. We use a right-handed Cartesian coordinate system with the three wind speed components, u, v, and w, aligned with the x, y, and z (the vertical) axes, respectively. The magnitude of the horizontal wind speed is thus \( U = (\bar{u}^2 + \bar{v}^2)^{1/2} \). The coordinate center is placed on the ground just downwind of the fence. Two length scales are used to describe the flow: the surface roughness length \( z_o \) and the height of the fence \( h \).

![Figure 23: Sketch of the turbulent flow around a 2D fence. The vertical plane studied in this work is also shown](image)

In the present work, we investigate the flow in a 2D vertical plane that extends 2.5 \( h \) vertically and \( \approx 11 \ h \) horizontally downstream of the fence. For simplicity, two main flow regions are defined in this plane: the ‘near-wake’ \( (x < 6 \ h) \) and the ‘far-wake’ \( (x > 6 \ h) \) regions. Although the fence and the vertical plane are 2D, the flow is not. We will describe the flow for different inflow directions in addition to the direction perpendicular to the fence (along the x-axis).
6.2.2 Inflow conditions

We start by assuming that the inflow can be described as atmospheric flow under flat and homogeneous conditions, in which the velocity profile can be estimated using the diabatic wind profile Stull (1988),

\[ U_o(z) = \frac{u_s}{\kappa} \left[ \ln \left( \frac{z}{z_0} \right) - \psi_m(z/L) \right], \tag{14} \]

where \( u_s \) is the friction velocity and \( \kappa \) the von Kármán constant (≈0.4). \( \psi_m \) is an extension to account for stability conditions that is a function of the dimensionless parameter \( z/L \), being \( L \) the Obukhov length. By using velocity and temperature fluctuations, we can compute \( u_s \) and \( L \) as

\[ u_s = \left( \frac{u'^2 + v'^2}{2} \right)^{1/2}, \tag{15} \]

\[ L = -\frac{u_s^3}{\kappa (g/T) \overline{w}/\Theta_v}, \tag{16} \]

where \( g \) is the acceleration due to gravity, \( T \) a reference temperature, \( \Theta_v \) the virtual potential temperature, the primes denote fluctuations around the time average, and the overbar a time average.

6.2.3 Shelter – two-dimensional theory

The shelter observations will be presented in terms of the speed-up \( U/U_o \) at a specific height \( z \). The speed-up can be written in the form

\[ \frac{U(z)}{U_o(z)} = 1 - \frac{\Delta U(z)}{U_o(h)} \frac{U_o(h)}{U_o(z)}, \tag{17} \]

where \( \Delta U(z) = U_o(z) - U(z) \). The term \( \Delta U(z)/U_o(h) \), which is the ratio of the velocity difference to the inflow velocity at the height \( h \), is the quantity predicted by the analytical theory of Counihan et al. (1974). They argued that the wake behind a 2D obstacle can be divided into three regions and that within the mixing region, which spreads from the top of the obstacle, the velocity is self-preserving with the form,

\[ \frac{\Delta U(z)}{U_o(h)} = \frac{C/(n+1)}{K h^2 U_o(h)^2} \left( \frac{x}{h} \right)^{n-1} \frac{d}{d\eta} \left[ \eta^2 {}_1 F_1 \left( \frac{2-n}{2+n}, \frac{n+4}{2+n}, \frac{-\eta^{n+2}}{(n+2)^2} \right) \right], \tag{18} \]

where \( C \) is a term related to the wake strength, which is assumed to be constant in the far wake (see more details below), \( K = 2 \pi^2 / \ln(h/z_o) \) is a measure of the ratio of shear to inertial stresses and thus related to the eddy viscosity \( \nu_e \), \( n \) is the shear exponent of the inflow’s vertical velocity profile, which for near-neutral conditions and close to the ground is \( \approx \ln(z/z_o)^{-1} \) Panofsky and Dutton (1984), \( {}_1 F_1 \) is the confluent hypergeometric function, \( \eta \) is a dimensionless length scale related to the depth of the mixing region, and \( I \) is an integral constant for the self-preserving solution of the wake in the mixing region. The latter two are expressed as

\[ I(n) = \frac{(1+n)(2+n)^{(4+n)/(2+n)}}{1+2n} \Gamma \left( \frac{4+n}{2+n} \right) \Gamma \left( \frac{1-n}{2+n} \right), \tag{19} \]

\[ \eta = \left( \frac{z}{h} \right) \left( \frac{K x}{h} \right)^{-1/(n+2)}, \tag{20} \]

where \( \Gamma \) is the Gamma function.

Equation (18) assumes \( \nu_e = K h U_o(h) \). Originally, it is not the velocity magnitude \( U(z) \) the quantity predicted by the theory but \( u(z) \) (here we assume it valid for the former). Counihan et al. (1974) showed that profiles of \( \frac{\Delta U(z)}{U_o(h)} \left( \frac{z}{h} \right) \) as function of \( \eta \) converge onto each other within the far-wake region \( 6 \leq x/h \leq 30 \) from full-scale measurements of the wind behind porous windbreaks and within the range \( 7.5 \leq x/h \leq 72 \) for a number of wind-tunnel measurements.
Based on Counihan et al.’s self-preserving theory and using wind-tunnel measurements of the wake behind 2D solid and porous fences, Perera Perera (1981) proposed the empirical relation,

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

where $\varphi$ is the fence’s porosity and $A$ is a constant ($= 9.75$). We speculate that because Eq. (21) is simpler and agrees better with Perera’s observations than Eq. (18) (the comparison is performed within the range $7.5 \leq x/h \leq 25$), Perera’s expression has become the basis of engineering obstacle models.

The solution to the term $\partial [\ldots] \over \partial n$ in Eq. (18) is unattractive but for the special case $n = 0$, it is simple ($= 2 \eta \exp (-0.25 \eta^2)$). The self-similar velocity profile $\Delta U(z) \over U_o(h)$ shows a maximum at $\eta(z/h \approx 1)$ and approaches a zero value with increasing $\eta$. For decreasing $n$ values, such an approach to zero occurs at smaller $\eta$ values and the profile’s maximum slightly decreases (only $7\%$ between $n = 0.14$ and 0). In addition, $I$ is not that sensitive to the shear exponent ($= 7.64$ and 7.08 for $n = 0.14$ and 0, respectively), and $C = C_h h^2 U_o(h)^2$ from pressure measurements on rectangular blocks in shear flows Counihan et al. (1974). Therefore, Eq. (18) can be simplified to

$$\Delta U(z) \over U_o(h) = \frac{C_h}{K I(n = 0.14)} \left( \frac{x}{h} \right)^{-1} 2 \eta \exp \left( -0.25 \eta^2 \right).$$

Counihan et al. (1974) chose $C_h = 0.8$ when analyzing measurements behind 2D blocks. Following the analysis by Taylor and Salmon (1993), $C_h$ corresponds to the wake moment coefficient. They provide some guidance for estimating it for 2D and 3D cases. Based on their review $C_h = B(1 - \varphi)$ with $0.2 \leq B \leq 0.8$ depending on the type of the obstacle.

### 6.3 Site and measurements

We aim at describing the effect of a full-scale obstacle on the atmospheric flow by measuring on a vertical plane downwind of a fence. The shelter can extend for more than $10 h$ and $2 h$ in the horizontal and vertical directions, respectively. We also want to analyze reconstructed and accurate wind fields with high spatial and temporal resolution within the vertical plane. Therefore, we need either a close-spaced array of masts or a measurement alternative based on remote sensing. We chose to use DTU’s WindScanner (WS) system, which is a lidar-based measuring system. In this section, we first describe the site, where the ‘fence experiment’ was conducted, the measurements from a meteorological mast, which was installed besides the fence to measure the inflow/undisturbed conditions, and the measurements from the WS system.

#### 6.3.1 Site

The ‘fence experiment’ took place at DTU’s test site at Risø, which is $\approx 7$ km north from Roskilde and $\approx 35$ km west from Copenhagen, Denmark (see Fig. 24). It was conducted during two periods: from March 10 to April 1 the fence was solid and from September 29 to October 2 2015 the fence was made porous. The terrain at the test site is slightly hilly and the surface is characterized as a mix between cropland, grassland, artificial land, and coast.

The fence was made of horizontal wooden panels with wooden beams on each side supporting the structure (see Fig. 25-bottom frames). For the second period of the experiment, the estimated fence porosity (ratio of the ‘pores’ to the total area) is 0.375. The fence is 3-m high, 30-m wide, and 0.04-m thick (the wooden vertical poles are 0.1-m thick). The center point of the fence has coordinates 694477.5E, 6175332N (UTM32 WGS32) and is $\approx 78$ m southeast of the Roskilde Fjord coastline. Due to land restrictions and the orientation of the coastline, the fence is oriented $\approx 42^\circ$ from the true north (winds from the direction $\approx 312^\circ$ are thus normal to the fence).

The slope of the terrain behind the fence was measured with a Trimble global positioning system (GPS) with a resolution of 0.1 m along two lines nearly normal to the fence from its corners. Figure 26-top illustrates the fence experiment and the instrumentation. We aim at scanning the
Figure 24: Location of the fence experiment on a digital surface model (UTM32 WGS84) of the area surrounding DTU’s test station at Risø, Denmark. Cropland and grassland are shown in green, cropland and artificial land in light brown, rural areas and buildings in brown color, and the waters from the fjord in light blue. The reference coordinate system is shown in red. In the bottom-right part of the figure, the location of DTU’s test site (black rectangle) on the island of Zealand, Denmark, is illustrated.

flow on a vertical plane downwind the fence as shown in Figs. 23 and 26. The bottom panel illustrates the positions where we want to measure (described in Sect. 6.3.3) and the terrain elevation along the scanning pattern. Note that the reference system is not at the fence center but 1.53 m southwest and so the corners of the fence are not at the same distance from the reference system (see Table 1). The height of the terrain above the fence base for the positions at which we want to measure the shelter is provided in Table 5 in the Appendix. The relative wind direction to the fence, $\theta$, is defined positively increasing clockwise.

6.3.2 Meteorological mast

A meteorological mast is deployed northeast of the fence and two Metek USA-1 sonic anemometers are placed on booms oriented towards the fence at 6 and 12 m above the ground and record time series of the three wind speed components and temperature at a frequency of 20 Hz. Data from both sonics are available for the entire duration of the fence experiment.

Mean and turbulence statistics are estimated over 10-min periods from the sonic measurements (we also analyze the sonic time series in shorter time periods as described in Sect. 6.4). The sonic times series are linearly detrended over the 10-min period, and mean and turbulence quantities, such as $u_*$ and $L$, are estimated from the 10-min statistics. The terms $T$ and $\bar{w}T'$ in Eq. (16) are estimated from the sonics’ temperature and kinematic heat flux, respectively. For the latter, we use the crosswind corrections of Liu et al. (2001).

6.3.3 Lidar measurements – the WindScanner system

Lidar basics The three velocity components on the vertical plane are measured using three short-range lidars that are synchronized both in time and space. These three devices conform the WS system. The instruments are based on a continuous-wave coherent lidar (Karlsson et al. 2000), which is capable of measuring the radial (or line-of-sight) speed and its direction (Sjöholm et al. 2014).

The lidars and, thus, the WS system do not perform point-like but volume measurements. The
volume depends on the probe length of each lidar, which is considered to be twice the Rayleigh length $z_R$. At focused distances of 28 and 42 m, the lidars operate with $z_R = 0.67$ and 1.52 m, respectively Sonnenschein and Horrigan (1971).

**Simulation of the WindScanner system** An optimized positioning for the three lidars of the WS system is a compromise between the size of the scanned area (or volume in which we want to measure), the error in wind speed (which increases with the size of the scanned area), and the wind speed components (which we are most interested in accurately measuring). As a lidar measures the line-of-sight velocity only, we need to deploy at least one of the instruments as far downwind as possible, so that under ‘ideal’ inflow conditions ($\theta \approx 0^\circ$) this unit (R2D3 in the solid fence setup) measures most of the $u$-velocity component at all positions on the vertical plane, and as close to the fence to avoid interference of the probe volume with the fence itself.

A CFD solver of the RANS equations (EllipSys) Sørensen (2003) with a standard $k$-$\varepsilon$ model was used to simulate the flow behind the fence (the solid setup only) and the CFD results were used to ‘simulate’ the flow field observed by the WS system including the effect of the lidars’ probe volume. The CFD simulation was performed using flat terrain with the condition $h/z_0 = 300$. A logarithmic wind profile in balance with the ground roughness was used as inlet condition with a wind direction $\theta = 0^\circ$. In order to correctly model the high near-fence velocity gradients, the CFD grid had a 0.03 m wall resolution, which was coarsened with distance to the wall. CFD results were extracted from the same vertical plane as scanned by the WS system.

Figure 27 shows both the CFD and the WS-system simulated flow assuming that the CFD results ‘follow’ the terrain elevation. As illustrated, the largest differences for the $u$-component occur close to the fence and at $z/h = 1.50$ but the relative error is highest for the vertical levels close to the ground. Similarly, for the $w$-component, the difference generally increases the closer to the fence and is highest at the two first vertical levels. These are the areas where the CFD simulation results show the highest gradients of $w$ and so we expect to have large uncertainty in
Figure 26: The fence experiment in the reference coordinate system. The positions of the fence (gray rectangle), the lidars (blue circles), the mast (black triangle and black thick line), scanning grid (red circles), and GPS measurements (cyan circles) are also illustrated both at the top (top) and side (bottom) views. The terrain elevation is also shown in the side view.

Figure 27: Simulation of the measurements of the WS system (solid lines) and the CFD simulation results (dashed lines) for $u$ (left frame) and $w$ (right frame) and several vertical levels.

A number of positions for the lidars were tested and the one shown in Fig. 26 and Table 1 was selected because it gave the lowest error for both the $u$- and $w$-velocity components 'simulated' by the WS system when compared to the CFD results. For the second period of the campaign, the lidars were swapped and their positions in the $x$-$y$ plane slightly changed (all positions less than 0.5 m except for the furthest lidar relative to the fence, which was re-located $\approx 3$ m away in the $y$-position).

**Experimental details** The scanning pattern on the vertical plane was decided based on the CFD simulation results and the regions where we are interested in measuring the shelter; e.g. we wanted to measure in both the near- and far-wake regions, and below and above the fence height.
Table 1: Coordinates of the instrumentation for the fence experiment

<table>
<thead>
<tr>
<th>Instrument</th>
<th>x [m]</th>
<th>y [m]</th>
<th>z [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2D1</td>
<td>2.43</td>
<td>-27.67</td>
<td>0.40</td>
</tr>
<tr>
<td>R2D2</td>
<td>2.36</td>
<td>26.96</td>
<td>0.40</td>
</tr>
<tr>
<td>R2D3</td>
<td>43.00</td>
<td>0</td>
<td>2.43</td>
</tr>
<tr>
<td>Sonics</td>
<td>0.06</td>
<td>31.91</td>
<td>6.12</td>
</tr>
<tr>
<td>Fence (southern corner)</td>
<td>0</td>
<td>-13.51</td>
<td>0, 3</td>
</tr>
<tr>
<td>Fence (northern corner)</td>
<td>0</td>
<td>16.53</td>
<td>0, 3</td>
</tr>
</tbody>
</table>

(up to \(z/h \approx 2.5\)). The lidars of the WS system were therefore set to synchronously scan from a position 1 m downwind the fence up to a distance of 10 \(h\) and at 7 different levels following the terrain elevation. Throughout the scan, the lidars were continuously acquiring line-of-sight velocity spectra at a sampling rate of \(\approx 49\) Hz. The spectra were gridded in 1 m cells and spatially averaged in each cell leading to 31 space and time averaged spectra per line. The final scanning grid has thus 31 \(\times\) 7 points in the \(x-z\) plane. The 7 vertical levels are at the heights \([0.21, 0.46, 0.71, 0.96, 1.46, 1.96, 2.46] h\). The 31 positions along the \(x\)-axis are given in Table 5 in the Appendix.

A 'full-scan', i.e. a complete measurement of all 217 grid positions, took \(\approx 39\) s for the first two days of the campaign (3 s to scan each line and 3 s to start with a new vertical level) and for the rest of campaign \(\approx 21\) s only, as the time that took for the WS system to start scanning at a new vertical level was reduced. During the second period of the campaign, one of the lidars had problems with the focus mechanism. This resulted in dislocations of the measurement points during the transition from vertical levels, which translated in measurements falling outside the corresponding cell. Therefore, to increase the amount of full-scans for the second period, we redefine the full-scan on a smaller scanning grid of 29 \(\times\) 7 points, i.e. excluding the grid points furthest and closest to the fence.

After the line-of-sight spectra are averaged in each cell, a series of post-processing steps were performed to first remove noise signals and, subsequently, a median frequency estimator was applied to derive the line-of-sight velocity in each spectrum using the technique by Angelou et al. Angelou et al. (2012). The minimum detectable speed of the WS system is \(\approx 0.15\) m s\(^{-1}\); thus, when the line-of-sight velocity is lower than this value, the WS system reports a zero line-of-sight velocity (this also occurs when no energy is detected). Thus, we filter out full-scans where line-of-sight velocities are zero or appear as peaks in the time series (for the latter using the method by Goring and Nikora (2002)) for each lidar and grid position.

The \(u\)-, \(v\)-, and \(w\)-velocity components are estimated at each grid position from the geometry of the scan (i.e. the grid position relative to that of the lidars) combined with the line-of-sight velocities of the lidars. A preliminary analysis of the estimations of \(w\) at the first two vertical levels showed unrealistic values because the line-of-sight of the lidars is almost perpendicular to the \(w\)-velocity component. Therefore, for all the positions in these two levels, we use the line-of-sight velocities of R2D1 and R2D3 only, which means that at these two levels we can only estimate \(u\) and \(v\).

The WS system was mostly operated when the sonic measurements indicated westerly winds and when there was no indication of rain. The measurements from the WS system are thus concentrated on few days as indicated in Table 2 with the amount of full-scans for each day.

### 6.4 Data analysis

#### 6.4.1 Sonic-lidar intercomparison

Besides the 10-min mean and turbulence statistics from the sonic measurements, we derive another set of sonic statistics based on the time period that the WS system takes to complete each full-scan (denoted by a \(\tilde{\text{\_\_\_}}\) symbol). Thus, we also know both the mean wind speed and direction, and their variability, within this shorter period.

The scanning grid point closest in space to the sonic anemometer at 6 m is at a height of \(\approx 6\) m.
<table>
<thead>
<tr>
<th>Date</th>
<th>No. of full-scans</th>
<th>porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 10</td>
<td>637</td>
<td>solid</td>
</tr>
<tr>
<td>March 11</td>
<td>712</td>
<td>solid</td>
</tr>
<tr>
<td>March 20</td>
<td>11</td>
<td>solid</td>
</tr>
<tr>
<td>March 26</td>
<td>84</td>
<td>solid</td>
</tr>
<tr>
<td>March 27</td>
<td>81</td>
<td>solid</td>
</tr>
<tr>
<td>April 01</td>
<td>27</td>
<td>solid</td>
</tr>
<tr>
<td>September 30</td>
<td>11</td>
<td>porous</td>
</tr>
<tr>
<td>October 01</td>
<td>107</td>
<td>porous</td>
</tr>
<tr>
<td>October 02</td>
<td>125</td>
<td>porous</td>
</tr>
</tbody>
</table>

Table 2: Amount of full-scans performed by the WS system for each day of the campaign and the fence porosity.

We compare the measurements from the WS system at this grid position with those from the 6-m sonic. This is not a fair comparison because the measurements from the WS system at each grid position are nearly ‘instantaneous’, i.e. it takes less than 0.1 s to scan each grid point (we will use a ~ symbol to refer to such measurements), whereas we use the full-scan period for the sonic measurements. However, the comparison will show us the conditions in which the flow at both positions is similar. Fig. 28 shows a scatter plot of such measurements for both periods of the campaign.

Figure 28: (Left) scatter plot of wind speed measurements from the 6-m sonic anemometer and the WS system for the scanning grid point closest to the fence and at height of ≈6 m. (Right) the difference between these two measurements as function of the relative wind direction observed by the 6-m sonic. Data recorded during the first period (solid fence) is shown in black and during the second period (porous fence) in red markers.

Figure 28-left illustrates the good agreement between the 6-m sonic and the WS system for the horizontal wind speed magnitude; the scatter is low and high for low and high wind speeds, respectively. Figure 28-right shows that the degree of scatter is a function of the relative wind direction; when the WS system measures downwind the fence (i.e. |θsonic| ≤ 90°), the scatter is much higher than for upwind conditions. Although the grid point used is ≈1 h above and ≈1 h downwind the fence, there seems to be a strong effect of the fence on the flow at this position, whereas the effect is nearly negligible for |θsonic| ≥ 90°. A similar analysis for downwind conditions using the grid point furthest away from the fence (≈32 m) and at the same vertical level shows a reduction of the scatter (not shown) as the shelter is low there (see Sect. 6.5). Figure 28-right also shows that most of the measurements are concentrated at θsonic ≈ −50° and that few data are recorded for winds perfectly normal to the fence.
6.4.2 Inflow conditions

The flow at the mast position, which we assume to be undisturbed by the fence for winds within the range $-75 \leq \theta \leq 75^\circ$, determines the inflow conditions that are necessary to estimate the speed-up due to shelter, i.e. the term $U_o(h)/U_o(z)$ in Eq. (17). Therefore, we need to estimate the surface conditions as a function of relative wind directions at the site.

Assuming, at first, that the inflow conditions at the mast correspond to those of homogenous flow over flat terrain, we estimate $z_o$ from Eq. (14) using 10-min mean and turbulence statistics from the sonic measurements. In this fashion we have two $z_o$ values derived either using the sonic anemometer at 6 m or that at 12 m for each 10-min period. For the computation of $\psi_m$, we use the forms in Peña Peña (2009). Table 3 shows the median of such $z_o$ estimations based on the 6- and 12-m sonic measurements for the whole month of March and September 2015 (for the specific conditions of both periods of the campaign) and for $10^\circ$ $\theta$ intervals (we use the 10-min mean sonic wind direction, i.e. $\theta_{sonic}$, to classify the 10-min sonic statistics into the relative direction intervals). As shown, for both periods $z_o$ increases with increasing $|\theta|$, as expected, due to the topography upstream the fence (see Fig. 24). Further, the difference in roughness lengths between both periods is relatively small indicating that, particularly at $\theta \approx 0^\circ$, $z_o$ is greatly influenced by the surface conditions of the fjord.

<table>
<thead>
<tr>
<th>$\theta \pm 5^\circ$</th>
<th>March $z_o$ [m]</th>
<th>No. of 10-min samples</th>
<th>September $z_o$ [m]</th>
<th>No. of 10-min samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-m $z_o$ [m]</td>
<td>12-m $z_o$ [m]</td>
<td></td>
<td>6-m $z_o$ [m]</td>
<td>12-m $z_o$ [m]</td>
</tr>
<tr>
<td>-90</td>
<td>0.0673</td>
<td>0.0785</td>
<td>176</td>
<td>0.0549</td>
</tr>
<tr>
<td>-80</td>
<td>0.0435</td>
<td>0.0542</td>
<td>174</td>
<td>0.0280</td>
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<tr>
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<td>0.0231</td>
<td>0.0173</td>
<td>174</td>
<td>0.0095</td>
</tr>
<tr>
<td>-60</td>
<td>0.0095</td>
<td>0.0070</td>
<td>116</td>
<td>0.0072</td>
</tr>
<tr>
<td>-50</td>
<td>0.0069</td>
<td>0.0095</td>
<td>114</td>
<td>0.0052</td>
</tr>
<tr>
<td>-40</td>
<td>0.0049</td>
<td>0.0075</td>
<td>148</td>
<td>0.0028</td>
</tr>
<tr>
<td>-30</td>
<td>0.0031</td>
<td>0.0051</td>
<td>183</td>
<td>0.0012</td>
</tr>
<tr>
<td>-20</td>
<td>0.0031</td>
<td>0.0036</td>
<td>61</td>
<td>0.0009</td>
</tr>
<tr>
<td>-10</td>
<td>0.0021</td>
<td>0.0033</td>
<td>40</td>
<td>0.0004</td>
</tr>
<tr>
<td>0</td>
<td>0.0014</td>
<td>0.0010</td>
<td>33</td>
<td>0.0009</td>
</tr>
<tr>
<td>10</td>
<td>0.0013</td>
<td>0.0026</td>
<td>61</td>
<td>0.0018</td>
</tr>
<tr>
<td>20</td>
<td>0.0014</td>
<td>0.0051</td>
<td>15</td>
<td>0.0030</td>
</tr>
<tr>
<td>30</td>
<td>0.0015</td>
<td>0.0043</td>
<td>43</td>
<td>0.0060</td>
</tr>
<tr>
<td>40</td>
<td>0.0020</td>
<td>0.0038</td>
<td>16</td>
<td>0.0121</td>
</tr>
<tr>
<td>50</td>
<td>0.0113</td>
<td>0.0447</td>
<td>10</td>
<td>0.0407</td>
</tr>
<tr>
<td>60</td>
<td>0.0280</td>
<td>0.0859</td>
<td>12</td>
<td>0.0975</td>
</tr>
<tr>
<td>70</td>
<td>0.0204</td>
<td>0.0778</td>
<td>34</td>
<td>0.0172</td>
</tr>
<tr>
<td>80</td>
<td>0.0149</td>
<td>0.0970</td>
<td>55</td>
<td>0.0151</td>
</tr>
<tr>
<td>90</td>
<td>0.0330</td>
<td>0.2586</td>
<td>73</td>
<td>0.0289</td>
</tr>
</tbody>
</table>

Table 3: Roughness length $z_o$ as function of the relative wind direction $\theta$ based on either the 6-m or the 12-m sonic anemometer measurements for both March and September 2015. The amount of 10-min samples is also shown.

It can be argued that $z_o$ should be estimated from Eq. (14) when the atmospheric conditions are near neutral, i.e. when $|z_o/L| \leq 0.01$, which leads to $\psi_m(z_o/L) \approx 0$, to avoid errors due to the uncertainties in the $\psi_m$ functions. However, only 17% of the 10-min periods are near neutral for $|\theta_{sonic}| \leq 90^\circ$, and so the uncertainty in the estimation of $z_o$ is too large. So, is it sufficient to describe the inflow using e.g. Eq. (14) with the $z_o$ values in Table 3 given that the terrain is not flat, the upstream conditions not homogeneous, and the atmospheric conditions generally not neutral? To answer this question, we define ‘case’ studies based on $\theta$ intervals and we select the data, which are included in each case, using the full-scan mean direction from the 6-m sonic anemometer, i.e. $\tilde{\theta}_{sonic}$ (see Table 4).

The case studies are selected so that each has a significant number of full-scan samples and that we can study the influence on the shelter of a wider $\theta$ interval (cases I and II), $\theta$ itself (cases
Table 4: The case studies defined for a number of θ intervals. Refer to the text for the explanation of the different columns in the table.

I and III–V), atmospheric stability (cases II and VI), and porosity (case VII). Table 4 provides an estimation of different parameters that are used to reproduce the inflow conditions for each case, which are also illustrated in Fig. 29-left. For each case, we:

1. ensemble-average the z_o values in Table 3 within the θ interval in Table 4 (we denote ensemble averages with the ⟨⟩ symbol),
2. estimate a ‘new’ friction velocity \( u_{est} \) with Eq. (14) assuming \( \psi_m(z/L) = 0 \) and using the sonic wind speed measurement at 6 m, ensemble-averaged from the sonic mean wind speeds within the full-scan period,
3. estimate the ‘mean’ inflow wind profile \( \langle U_o(z) \rangle \) using Eq. (14) assuming \( \psi_m(z/L) = 0 \) (solid color lines in Fig. 29-left) as

As shown, the estimations of the inflow profiles are in good agreement with the sonic measurements (an absolute error of 0.18 m s\(^{-1}\) is computed at 12 m for case V as the largest of all cases). We therefore assume that, although present, the topographic effects at the mast position within the heights 6–12 m can be neglected for these θ ranges. The inflow is thus well described by the logarithmic wind profile.

Figure 29: (Left) Inflow conditions for the case studies. The circle markers indicate the ensemble-averaged sonic measurements \( \langle \tilde{U} \rangle_{\text{sonic}} \) ± the standard error in the error bar and the lines the estimations of the mean inflow conditions \( \langle U_o(z) \rangle \) (see text for details). (Right) normalized distribution (NPD) of the relative wind direction from the 6-m sonic θ_{sonic} for the case studies.

In addition, Fig. 29-left shows three more profiles for case I. The black dashed line shows the mean inflow conditions but using the ensemble-average \( u_* \) of \( u_* \) values estimated from the 6-m

\(^{1}\)Although this is not an ensemble average per definition, we use the () symbol because it results from the ensemble-averaged roughness length \( z_o \).
sonic anemometer measurements with Eq. (15) within the full-scan period, i.e. \( \langle \tilde{u} \rangle \). In this case, there is a systematic underestimation of the inflow wind speed because \( \langle \tilde{u} \rangle \) is about 13% lower than \( u_{est} \) (the latter is given in Table 4). The results in the black dash-dotted line are obtained similarly to those in the solid lines but using the sonic anemometer measurements at 12 m and the \( z_o \) derived from the observations at that height. Therefore, the estimated inflow wind speed at 12 m is equal to the ensemble-average sonic wind speed at the same height. The results in the black dotted line are found with the same methodology as that used for the results in the dashed line but with the sonic anemometer measurements at 12 m. From these three results, we confirm: first, that turbulent fluxes estimated in the short period of the full-scan are not adequate for deriving the inflow conditions (see the work of Lenschow et al. (1994)) and, second, that similar results are obtained when using \( z_o \) estimations based on either 6 or 12-m sonic anemometer measurements. This also gives us an idea of the small effect that the internal boundary layer (developed at the coastline) has on the inflow wind speed profile at the mast position and within the heights between the sonic measurements.

For case VI, a second mean inflow profile (magenta dashed line) is shown in Fig. 29-left. Case VI is similar to case II but we narrow the analysis to stable conditions \( z/L \geq 0.01 \) from the ‘concurrent’2 10-min derived turbulence sonic estimates at 6 m. \( u_{est} \) can be computed as in Eq. (23) and, in addition, the correction due to atmospheric stability can be included (the result is the second value for the \( u_{est} \) column in Table 4). Thus, the magenta dashed line shows the mean inflow profile using Eq. (24) with this new \( u_{est} \) value, which overestimates the mean wind speed at 12 m by 0.16 m s\(^{-1}\) only.

For each case in Table 4, we also include the average dimensionless stability \( \langle z/L \rangle \) value, which is found by ensemble-averaging the 10-min turbulence fluxes from the 6-m sonic anemometer that are ‘concurrent’ with the time of the full-scans. As shown, the atmosphere for the ‘solid fence’ cases is in average stable, except for case V, which corresponds to the most northern winds, and for the ‘porous fence’ case the atmosphere is unstable. Interestingly, although we do not narrow the filtering criteria to stable conditions for case IV, \( \langle z/L \rangle \) is higher for this case than for case VI.

Figure 29-right shows that the distribution of \( \theta_{sonic} \) values for each case is not uniform and that the center of the interval, in most cases, differs from the mean of the relative directions within the interval; thus these distributions should be taken into account when evaluating models with the particular cases. We provide the values of such distributions in Table 6 in the Appendix.

6.5 Shelter results

6.5.1 Speed-up behind the fence

As for the inflow conditions, we classify the data from the full-scans of the WS system into the cases in Table 4 using the \( \theta_{sonic} \) values. The horizontal wind speeds from the WS system are then ensemble-averaged within each case, \( \langle \tilde{U}(z)_{WS} \rangle \), and so the speed-up is estimated by normalizing these averages by the case-correspondent ‘mean’ inflow profile (described in Sec. 6.4.2).

The plots in Fig. 30 illustrate the speed-up for each case. Although \( \theta_{sonic} \) does not uniformly distribute within the chosen relative direction intervals, the effect of the fence on the flow for varying \( \theta \) values is well observed, particularly from the results between cases I, III and IV (three left frames from the top). Case I, as expected, shows the deepest shelter effect of these three cases, which diminishes when increasing |\( \theta \)| and, for case IV, the effect of the fence is only noticed for \( x/h \geq 3 \). For case II, which is defined similar to case I but for a broader \( \theta \) interval (so it has a higher amount of full-scans), the speed-up is smoother and slightly deeper than that for case I but the differences are not large. This is most probably due to the concentration of full-scans at \( \theta_{sonic} \approx 10^\circ \) in both cases. Case VI, the ‘stable’ case II, also shows a similar behavior but with slightly deeper shelter effects than case II. Case V, similarly defined as case III but with \( \theta \) centered at 30°, shows reductions up to 50% for \( x/h \leq 4 \) as case III also does. Case VII, which is comparable to case III but for a different porosity, does not show speed-ups close to zero but the shelter seems to extend further away from the fence.

\(^2\)It is written in quotation marks because a full-scan take less than 10 min to be performed.
Figure 30: Averaged speed-up $(\tilde{U}(z)_{WS})/(U_o(z))$ on the vertical plane behind the fence for a number of cases. Vectors indicate the magnitude and direction of the ensemble-averaged $u$-velocity component measured by the WS system.

In addition, for cases I–III and VI we notice a small region where the speed-up is larger than one, located at $x/h \approx 2.5$ and $z/h \approx 2.5$. High speed-ups within the range $1 \leq x/h \leq 4$ are also observed for some of the other cases in Figs. 31 and 32. These figures illustrate the behavior of the speed-up (taking into account the sign of $u$) with distances downstream the fence, for the seven different levels, and for the seven cases. These high speed-ups are not distinguishable in cases V and IV in Fig. 30 because we deliberately truncate the speed-up to 1 for visual purposes. In the plots of Fig. 31, the high speed-up is clearly observed in the results for case IV for nearly all vertical levels, and for $z/h = 2.46$ (Fig. 32), it is visible for all cases where the fence is solid. In Fig. 33, we show this high speed-up from the CFD simulation results, which were used to estimate the wind speed error of the WS system in Sect. 6.3.3. The CFD simulation was performed over flat terrain without roughness changes and so it is the fence itself what causes the increased vertical velocity shear. Further, the results in Fig. 31 for case IV, in which the fence has the smallest effect on the vertical plane for $z/h \leq 0.71$, show that the speed-up is $\approx 1$ for $x/h \geq 7$. This shows us that the effect of the topography on the flow is small at all scan positions on the vertical plane relative to that at the mast position. Interestingly, for case IV, the magnitude of the reverse flow is much higher than that of the other cases when $x/h \lesssim 2.5$ and $z/h \lesssim 0.46$.

In Fig. 30, the direction and magnitude of the ensemble-averaged $u$-velocity component measured by the WS system is also illustrated. A region of reverse flow is visible for all cases when the fence is solid. This region is also shown in Fig. 33 but for the CFD results it extends much further downstream because the simulation is performed for $\theta = 0^\circ$ only.

The results in Figs. 31 and 32 confirm those in Fig. 30; for the solid setup, case VI generally shows the highest shelter in the far wake, systematically followed by cases II, I, III, V, and IV, as expected, due to the relative inflow wind directions. Interestingly, the behavior of the shelter for case VII follows that of cases I, II and VI in the far wake, does not strongly vary below the fence height in the near-wake region, and is the only case without reverse flow. For all the other cases, reverse flow can be distinguished and vanishes only at $z/h \geq 0.96$. The behavior of the
Figure 31: Averaged speed-up $(\text{sgn}(\tilde{u}) \tilde{U}(z))/\langle U_o(z) \rangle$ on each vertical level behind the fence for a number of cases. ± the standard error is shown in the error bars.

speed-up with distance from the fence is similar for cases I, II and VI with the largest differences at $z/h = 0.21$ and $x/h \leq 5$, where the reverse flow peaks in magnitude (the peak is also seen in a lesser degree on the observations at $z/h = 0.46$ and $0.71$). The behavior of this peak is very similar for cases II and VI, which use the same relative direction interval.

Cases III and V have a similar speed-up behavior; case V systematically showing less shelter and so the differences are most probably due to the different distribution of $\theta$ values. The average
speed-up as function of distance from the fence and for each level and case are presented in Tables 7–13 in the Appendix.

**Figure 32:** Same as Fig. 31 but for $z/h = 2.46$

**Figure 33:** Velocity vector downwind the fence based on the CFD simulation results for $\theta = 0^\circ$

### 6.5.2 Self-preserving velocity profiles

Using the shelter observations from the cases in which the $\theta$ interval is center at $0^\circ$ (cases I, II, and VI), we compute the self-preserving forms of Counihan et al. (1974) (Sect. 6.2) and illustrate them in Fig. 34. For the three cases, we:

1. estimate a ‘mean’ shear exponent $\langle n \rangle$ for each case using the case-concurrent ensemble-average sonic measurements and the power law for the wind profile

   \[
   \langle n \rangle = \ln \left( \frac{\langle \tilde{U}_{\text{sonic}}(z = 6 \text{ m}) \rangle}{\langle \tilde{U}_{\text{sonic}}(z = 12 \text{ m}) \rangle} \right) / \ln(6 \text{ m}/12 \text{ m}),
   \]
   \[(25)\]

2. compute a ‘mean’ $K$ using the average roughness values in Table 4, i.e. $\langle K \rangle = 2 \kappa^2 / \ln(h/\langle z_o \rangle)$,

3. use the estimations of the mean inflow, i.e. Eq. (24), at the vertical levels and at $z = h$ to compute the average self-similar profiles,

   \[
   \langle \Delta U(z) \rangle \left( \frac{x}{h} \right) \left( \frac{1}{h} \right) = \frac{\langle U_o(z) \rangle - \langle \tilde{U}(z) \rangle_{\text{WS}}}{\langle U_o(h) \rangle} \left( \frac{x}{h} \right),
   \]
   \[(26)\]

4. estimate a ‘mean’ $\eta$ parameter, $\langle \eta \rangle$, based on Eq. (20) using $\langle K \rangle$ and $\langle n \rangle$.

The plots in Fig. 34 show the self-preserving profiles for a number of downwind distances; near-wake profiles ($x/h < 5.6$) in grey markers other than circles and far-wake profiles ($x/h > 6.24$) in non-grey circles. The result of Eq. (21) with $A = 9.75$ is also shown. In addition, Eq. (22) is fit to the far-wake profiles (i.e. $C_\eta$ is estimated in a least-squares sense) and the result illustrated as well.
Generally for the three cases, the profiles in the near wake do not converge onto each other, whereas those in the far wake do, as predicted by Counihan et al. Counihan et al. (1974), particularly for cases II and VI with the broad direction interval. Equation (22) with the adjusted $C_h$ value agrees better with the profiles compared with Eq. (21), particularly in the region where the term $\langle [\Delta U(z)]/\langle U_o(h) \rangle \rangle (x/h)$ peaks (vertical levels below $h$), due to the low $C_h$ value used. For these cases, shelter estimations based on the expression of Perera will result in a general overestimation of the speed-up in the area below the fence height. Taylor and Salmon (1993) assume that $A = \Lambda C_h$ in Eq. (21), being $A$ a constant (for the special case of $C_h = 0.8$, $\Lambda = 12.19$). Following, analogically, the path we use to obtain Eq. (22), it becomes evident that $\Lambda$ might be also a function of $K$ and $I(n)$, i.e. of the eddy viscosity and shear characteristics of the flow.

The adjusted $C_h$ value in Eq. (22) changes considerably for these three cases. For the narrow direction interval (case I) it is nearly half the value recommended by Taylor and Salmon Taylor and Salmon (1993) for 2D fences and increases the broader the interval. The increase of $C_h$ in case II compared to case I can be explained by the characteristics of the distribution of $\theta$ in Fig. 29-right; the ensemble-average relative wind direction in case I is 6.27° and in case II is 0.39°, which partly explains the larger effect of the fence on the flow for case II. However, the effect on the flow is larger in case VI with an average relative wind direction of −12.70°; thus here the stable atmospheric conditions might be responsible for the increase in $C_h$ and the deeper wake. Using $\langle \Delta U(z) \rangle = \langle U_o(z) \rangle - \langle U(z) \rangle_{WS}$ instead of $\langle \Delta U(z) \rangle = \langle U_o(z) \rangle - \langle U(z) \rangle_{WS}$, as originally proposed by Counihan et al. Counihan et al. (1974), results in nearly the same profiles (not shown) but they do not converge as sound as those in Fig. 34.

Figure 34: Self-preserving velocity profiles for cases I, II, and VI for a number of downwind distances (see details in the text). Results from Eqs. (21) and (22) are also shown.
6.6 Conclusions and discussion

Full-scale field measurements of the flow on a vertical plane behind a solid fence are presented. The measurements were conducted by the short-range WS system, in which three time- and spatial-synchronized continuous-wave lidars measure the 3D wind vector. The measurements from the WS system agree well with sonic measurements from a nearby mast when the wind is not largely disturbed by the fence, although the measurement of the WS system (at the position of the scanning grid used for the comparison) is a close to ‘instantaneous’ record, whereas the sonic value is the $\approx 21–39$-s average of 20 Hz records. Simulation of the measurements from the WS system, taking into account the lidar’s probe volume and based on a CFD-RANS computation of the flow behind the fence, reveals that the WS system tends to underestimate the magnitude of the $u$-velocity component specially close to and above the fence ($x/h \lesssim 4$ and $z/h > 1$). This is mostly due to the combination of the high vertical velocity gradient simulated by the RANS-based model and the large probe volume of the lidar furthest downwind from the fence. By placing this lidar closer to the fence, the lidar error decreases but the far-wake region cannot be measured.

A number of speed-up cases are defined based on relative direction intervals from the sonic measurements. The speed-up depends on the inflow conditions, which we assume (partly due to the good agreement between the WS system and the sonic anemometer measurements at 6 m) can be derived from the mast measurements. In addition, we assume the topographic effects at each of the positions on the vertical plane to be similar to those at the mast position at the same height, as the speed-up approaches one for the case where the fence effect is lower on the flow (case IV) at $x/h \gtrsim 6$ and for all vertical levels. Between the sonic measurement levels (6–12 m), the inflow conditions for each case are well described by the logarithmic wind profile using direction-dependent roughness length values estimated from the 10-min sonic anemometer records. At the mast position and between the sonic measurement levels, orographic effects can thus be negligible but the effect of the sea-to-land roughness change upwind the fence is perhaps more important. At the fence position ($\approx 78$ m from the coast), turbulence characteristics are in transition from the upwind and the downwind conditions up to a height of $\approx 8$ m, the mean wind is in transition up to $z \approx 2.8$ m, and the wind profile is in equilibrium with the land surface up to $z \approx 0.56$ m (these values are estimated from the work of Floors et al. (2011)). Therefore, inflow conditions derived from the mast measurements are related mostly to the flow characteristics upwind the closest sea-to-land roughness change, and up to the furthest distance from this roughness change where measurements from the WS system are performed (i.e. $\approx 110$ m), the wind profile will be in equilibrium with the new surface within the first $\approx 0.77$ m only. When evaluating models with the speed-up measurements, topographic effects can be added using the terrain information we include. In addition, we provide all the necessary data to derive the inflow conditions that we use to compute the speed-ups; these can thus be re-computed with other inflow conditions if found necessary.

The speed-up behind the fence follows the expected behavior; for increasing relative wind directions, the flow is less disturbed by the fence, and within the near-wake region, the porous fence has a lower effect on the flow than the solid fence. However, for future model evaluation, the distribution of relative wind direction needs to be taken into account, as this is not uniform and its effects are well noticed. When comparing the near-neutral with the stable case defined with the same relative direction interval, we observe a deeper effect of the fence on the flow for the latter. Comparison with advanced CFD models are encouraged to distinguish if this effect is a result of atmospheric stability or of the distribution of relative wind directions. For all cases, the fence clearly reduces the wind speed when $z/h \leq 1.5$, and for some cases and depending on the vertical level, the fence speeds up the flow.

The velocity deficit profiles using self-preserving forms within the far-wake region ($x/h > 6.24$) converge onto each other as predicted by Counihan et al. (1974). Their solution (in a simplified version) agrees better with the self-preserving velocity profiles than the well-known empirical formula of Perera (1981), which overestimates the effect of the fence on the flow below the fence height. This is mainly due to a reduction of the wake momentum coefficient compared to the value used for 2D obstacles. The work of Counihan et
al. and Perera is mostly based on wind-tunnel studies, where the flow is nearly perpendicular to the obstacle. Evaluation of models with the measurements could provide more insights about the implementation of 3D effects on analytical solutions and the dependency of the wake momentum coefficient on relative wind directions.

Acknowledgments

Funding from the Energy Technology Development and Demonstration Program (EUDP) from Denmark to both the IEA Task 27 ‘small wind turbines in high turbulence sites’ and the ‘Online WAsP’ project (www.mywindturbine.com) are acknowledged. We would also like to thank the WindScanner team and the Test and Measurements section at DTU Wind Energy for helping us conducting the experiment.

Appendix

The terrain elevation above the fence base and at the WS system’s scanning grid positions is provided in Table 5. The distribution of relative wind directions for the case studies is shown in Table 6 and the average speed-up results in Tables 7–13.

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| x [m] | 30.70 | 31.71 | 32.40 |
|-------|-------|-------|
| z [m] | 1.28  | 1.34  | 1.38  |

*Table 5: Terrain elevation above the fence base at the scanning grid positions*
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Table 6: Normalized distribution of relative wind directions per case

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Table 7: Average speed-ups for each position of the WS system’s scanning grid for $z/h = 0.21$

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Table 8: Average speed-ups for each position of the WS system’s scanning grid for $z/h = 0.46$

<table>
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Table 9: Average speed-ups for each position of the WS system’s scanning grid for $z/h = 0.71$

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<td>case III</td>
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<td>case V</td>
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<tr>
<td>case VI</td>
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<td>0.80</td>
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<tr>
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<td>0.81</td>
<td>-</td>
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Table 8: Average speed-ups for each position of the WS system’s scanning grid for $z/h = 0.46$

<table>
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<th>9.25</th>
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<td>0.73</td>
<td>0.76</td>
<td>0.78</td>
<td>0.78</td>
<td>0.80</td>
<td>0.80</td>
<td>0.81</td>
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<td>0.71</td>
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<td>0.79</td>
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<td>0.78</td>
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Table 9: Average speed-ups for each position of the WS system’s scanning grid for $z/h = 0.71$
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Table 10: Average speed-ups for each position of the WS system’s scanning grid for \( z/h = 0.96 \)

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Table 11: Average speed-ups for each position of the WS system’s scanning grid for \( z/h = 1.46 \)

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Table 11: Average speed-ups for each position of the WS system’s scanning grid for \( z/h = 1.46 \)
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Table 12: Average speed-ups for each position of the WS system’s scanning grid for $z/h = 1.96$

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Table 13: Average speed-ups for each position of the WS system’s scanning grid for $z/h = 2.46$
7 Evaluation of the obstacle models

Evaluation of the models is performed using the measurements from the fence experiment described in Sect. 6, i.e., the six ‘cases’ in Tables –. We use the CFD-RANS model described in Sect. 3, WEMOD (Sect. 2.3), and WAsP-shelter (Sect. 2.2) to simulate the shelter due to the fence. No topography effects are taken into account in any of the models’ results.

7.1 CFD-RANS setup and preliminary results

The CFD computational grid is similar to that described in Sect. 3.3. The model domain has a height of 60 m, width of 300 m and length of 400 m. The fence has a height of 3 m and width of 30 m. The frontal areal of the fence occupies 0.5% of the cross-sectional area of the domain indicating that blockage from the domain boundaries has little influence. The fence is placed 40 m from the inlet; providing a long (360 m) downstream fetch for the wake to recover before reaching the outlet of the domain.

The CFD domain is divided into 1494 blocks each of \(16^3\) cells. The domain has a length of 12 blocks in the \(x\)-direction, a width of 10 blocks in the \(y\)-direction and a height of 13 blocks. Since no mesh block is needed at the fence location a total of 1494 blocks or 6.1 million cells are used.

A rectangular grid stretched towards the walls was used for the fence simulations. In order to capture the high velocity gradients the near-wall grid cells are only 0.03 m tall and coarsen with distance to the wall. Downstream of the fence the vertical grid resolution is kept in order to accurately model the development of the obstacle wake. Due to the mesh topology the fence has a thickness of 0.5 m. This was done to get a gradual coarsening of the grid cells necessary to achieve fast convergence of the CFD simulations. The coordinate system used has origin at the bottom downstream edge of the fence. The same roughness values for the ground walls are used for the fence surfaces. In total 9 CFD simulations of the flow over the fence were performed for relative angles from 0\(^\circ\) up to 80\(^\circ\) every 10\(^\circ\) with the condition \(h/z_0 = 300\).

Figure 35 shows the inflow velocity profile in the CFD simulations together with that at the ‘outlet’ (\(x/h = 50\)) for the relative direction perpendicular to the fence \(\theta = 0^\circ\). As illustrated, at \(x/h = 50\) the velocity is still highly disturbed by the fence (we will not see this impact in the observations due to the variability of the wind direction).

![Figure 35](image)

Figure 35: Inflow and outlet (\(x/h = 50\)) velocity profiles of the CFD-RANS simulations

Figure 36 shows the speed-up resulting from the CFD simulation for the same condition \(\theta = 0^\circ\) but using the longitudinal wind speed component \(u(z)\) to distinguish the areas of reverse flow.
For $z/h \leq 0.96$ the flow is reverse close to the fence and it can take up to $\approx 5-11$ obstacle heights to align with the inflow and this ‘alignment’ depends on the vertical level analyzed. Between $z/h = 0.96$ and $z/h = 1.46$ the speed-up changes dramatically close to the obstacle due to the high vertical velocity shear (see Fig. 33). For $z/h \geq 1.96$ the speed-up is above one indicating that the fence has a ‘positive’ effect on the flow.

**Figure 36:** The speed-up $u(z)/U_o(z)$ from the results of the CFD simulations at each of the vertical levels of the fence experiment as function of downstream distance for $\theta = 0^\circ$.

Figure 37 also shows the speed-up from the CFD simulations as a function of downstream distance from the fence but for a number of relative directions for the first vertical level measured in the fence experiment. The speed-up in this case is based on both the longitudinal component of both the inflow $u_o$ and the downstream value $u$. As shown within $\approx 40-60^\circ$ and within a range of two to three obstacle heights the speed-up jumps abruptly from low to high values as the flow does not get disturbed by the fence any longer. This high jumps might take "sharp patterns" when CFD results are averaged together within a direction interval if the center of the interval is other than $0^\circ$.

**Figure 37:** The speed-up $u(z)/u_o(z)$ from the results of the CFD simulations at the first vertical level ($z/h = 0.21$) of the fence experiment as function of the relative direction $\theta$. 

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7.2 WAsP-shelter and WEMOD setups and preliminary results

For WEMOD we simulate the shelter at all scanning positions of the fence experiment for a large range of $\theta$s, i.e., [-90°:1°:90°]. We use the roughness-length description in Table 3 and estimate a roughness for each simulated $\theta$ value by linear interpolation. A similar procedure is performed for the WAsP-shelter simulations but the angular resolution is slightly higher (1.1°).

Figure 38 shows the speed-up resulting from the simulations using WEMOD and WAsP-shelter for the same condition $\theta = 0°$ assuming the results from these models are in terms of the quantity $\text{sign}(u) U(z)/U_o(z)$ so that the reverse flow can be distinguished. For $z/h < 0.96$ the flow is reverse and it can take up to $\approx 4$ obstacle heights to become positive depending on the vertical level analyzed. One important difference between these results and those for CFD in Fig. 36 is that for $z/h = 0.96$ the fence strongly blocks the flow from the CFD view, whereas in WAsP-shelter and WEMOD the fence does not block the flow much close to the fence.

Figure 39 also shows the speed-up from the WEMOD and WAsP-shelter simulations as a function of downstream distance from the fence but for a number of relative directions for the first vertical level measured in the fence experiment. As shown the speed-up follows nearly the same form with varying $\theta$, the effect of the fence being noticed closer to the fence the higher $\theta$ becomes.

7.3 Results for the fence experiment cases

For each of the cases and each of the models there are three types of results for the speed-up $\text{sign}(u) U(z)/U_o(z)$. The first one (shown in dotted lines) refers to the simulation results at the center of the interval of relative directions (e.g., when $\theta = 0°$ for case I). The second one (in dashed lines) refers to the result of ensemble-averaging the speed-ups simulated for each direction within the direction interval of the case, i.e. taking into account the direction distribution in Table 6. The third one (in solid lines) also takes into account the direction variability within the time period of each of the individual ‘full-scans’ based on the 20 Hz sonic data. For simplification, the variability within the full-scan period is assumed to be Gaussian-distributed. The solid line is therefore the
result of ensemble-averaging speed-ups for each of the relative directions within the direction interval, which each is Gaussian-weighted based on the standard deviation of the sonic relative direction within the time period of the full-scan.

7.3.1 Case I

Figure 40 shows the model results of case I for each of the vertical levels. In general, the impact of the post-processing of the results is only evident in the CFD simulations, in particular when comparing the result for the center of the interval and that using the direction distribution within the interval (only slight differences are found between this and the result when the direction variability within the full-scan period is taken into account). The results between WEMOD and WAsP-shelter are nearly identical for $z/h \geq 0.96$ and for $z/h < 0.96$ the only disagree for $x/h \leq 6$ due to the shelter limitations artificially imposed in WAsP-shelter.

Interestingly, the CFD results (the third type) approach those from WEMOD and WAsP-shelter at all vertical levels for $x/h \leq 6$, i.e. in the far wake. The comparison of the models with the results depends generally on the position we look at on the vertical plane. Close to the fence (in the near wake), $x/h \leq 4$, the CFD results agree better with the observations than the analytical models, whereas for $x/h \leq 4$ the results from the analytical models (in particular WEMOD for the region $4 \leq x/h \leq 5$) are in better agreement with the observations than the CFD results. The speed-up peak in the near-wake is not captured by the analytical models for $z/h \leq 0.46$, and also in the near-wake and for $z/h \geq 0.71$, the speed-up is generally underestimated by the analytical models and do not follow the behavior of the observations.

7.3.2 Case II

Figure 41 shows the results of case II for each of the vertical levels. In general, the model results are very similar compared to those of case I but in this case, the results from the analytical models and the CFD simulations are both in better agreement with the observations; the observations do not change much compared to those of case I but the second and third type of model results do. For this case and for $z/h \leq 0.96$, we can notice differences between the first and second type of results when using WEMOD and WAsP-shelter, which is attributed to the broader direction interval compared to case I. The results for the center of the direction interval are of course the
same as those for case I.

It is interesting to notice that particularly for the more complex model (the CFD simulation), the differences in the second and third type of results, when comparing cases I and II, are large (the speed up can easily increase by a factor of 2). This also tells us how important is to simulate the whole range of relative directions within the direction interval used for the analysis of the observations. Also both cases I and II show that the degree of shelter is much lower than what one might think from the CFD model results, if only the direction in the center of the interval is used (the speed-up at $z/h = 2.46$ is $\approx 0.75$ for $x/h = 11$, whereas it is $\approx 1$ when comparing the first and second type of CFD results).

7.3.3 Case III

Figure 42 shows the results of case III for each of the vertical levels. In general, the the CFD results follow better the behavior of the observations than the analytical models and they are much better in the near wake region for $z/h \leq 0.96$. The third type of results from the analytical models are, however, better than those from any type of CFD results in the far wake. For cases I and II, the first type of results were always showing higher shelter compared to the other two types for all models, whereas in case III and within some regions, the first type of results can show less shelter (e.g the CFD results for $z/h \leq 0.46$ and $x/h \lesssim 2$ or the WEMOD results for $z/h = 0.96$ and $x/h \lesssim 2$).

Also in general, the CFD results underestimate the shelter (the opposite behavior was observed for cases I and II), whereas the analytical models tend to overestimate the shelter as they also do for cases I and II. It is not that clear from the CFD results whether the third type of results are better than the first type.

7.3.4 Case IV

Figure 43 shows the results of case IV for each of the vertical levels. In general, the CFD simulations (third type of results) capture well the behavior of the observed speed-up for all vertical levels and seem to have the lowest error (the other type of CFD results show larger differences particularly in the near wake). The analytical models less accurately follow the behavior of the observed speed-up and for both models, the first type of results generally agree better with the observations, being WAsP-shelter perhaps more accurate than WEMOD within the region $2 \lesssim x/h \lesssim 6$.

7.3.5 Case V

Figure 44 shows the results of case V for each of the vertical levels. This case is the only one where model simulations using the first type of results (i.e. using only the simulation at the center of the relative direction interval) are systematically closer to the observations of the speed-up, particularly for the CFD results. Interestingly for this case, the model predicted shelter from the first type of results is always lower than for the other types, whereas for case III, which is similar to case V but for positive relative direction, the first type of results always predicted less shelter than the other types.

7.3.6 Case VI

Figure 45 shows the results of case VI for each of the vertical levels. In general, all model results of the second and third type show very agreement with the observed speed-up in the far-wake region ($x/h \geq 6$) and for all vertical levels. In particular, the CFD simulation using the second or third type of results show very good agreement with the observed speed-ups at all vertical levels and all downstream distances; for cases I and II, which are similar to case VI, the models tend to over-predict the shelter but for this case (the ‘stable’ case II) the good matching is the result of the more pronounced shelter in the observations.
7.4 WAsP-shelter model error and uncertainty

Here we try to come up with an estimation of the error and the uncertainty of WAsP-shelter as this is the model used in Online WAsP. To estimate the speed-up of the model, we use all full-scans performed during the Fence experiment within the interval \( \theta \leq 0 \pm 75^\circ \). The sonic mean wind direction within each full-scan is used to run the model and so the results in Fig. 46 show the ensemble-average of speed-ups based on both observations and runs for each vertical level measured in the experiment.

As expected, for both observations and model, the shelter is higher the closer to the fence and to the ground; already at \( z/h = 0.71 \) there is some reverse flow, which can be nearly as high in magnitude as the inflow for the height closest to the ground. Also, as illustrated, for this broad relative direction interval and when compared to the observations, WAsP-shelter tends to underestimatethe shelter for \( x/h \lesssim 3 \) (due to the shelter limitations artificially imposed in the model), whereas it tends to overestimate it for \( x/h \gtrsim 4 \). Based on these results together with those in Fig. 2, we can confirm that in the region where the model is recommended for use for wind predictions, WAsP-shelter tends to overestimate the actual shelter due to obstacles.

We can also plot the error between the modeled and observed ensemble-averaged wind speed and see how it behaves with downstream distances and for the different vertical levels. This is shown in Fig. 47 where the markers represent the absolute error (in percentage) between model and observations normalized by the inflow value (such normalization is performed for applied use in Online WAsP). The inflow value at each height is estimated using the procedure in Sect. 6.4.2 but for the broad range of relative wind directions.

As illustrated, the error is highest close to the fence \((x/h \lesssim 4)\) and for greater distances, the error is less than 20% for all vertical levels. We use the results for \( x/h \geq 4.5 \) to fit an analytical model for the error. Using a least-squares a good approximation of the error is given as

\[
e_{(m-o)/free} = c_1 (z/h)c_2 \exp[c_3 (x/h)c_4],
\]

with \( c_1 = -0.0868, c_2 = -0.4836, c_3 = -0.000755 \), and \( c_4 = 3.2378 \).

Equation 27 is not that interesting for applied use. From Figs. 46 and 47, it is clear that the error of the model is low when the predicted shelter by the model is also low. A much simpler approach to the quantification of the error is therefore to quantify it as a percentage of the shelter predicted by the model. Figure 48 shows the behavior with downstream distance of half of the shelter predicted by WAsP-shelter for the broad direction interval and for different vertical levels.

From this much simpler analysis, the error in WAsP-shelter decreases for \( x/h \lesssim 4 \); at \( x/h = 4 \) it is \( \approx 27\% \) for \( z/h \leq 0.71 \), \( \approx 6\% \) for \( z/h = 1.46 \) and less than 1\% for the vertical levels above, which are sort of the numbers we get when analyzing the error in Fig. 47. Close to the fence \( x/h \lesssim 4 \) we should not use WAsP-shelter anyway so it might be meaningless to provide an error estimation within this region.

But what is the uncertainty of the WAsP-shelter model? We believe that we can provide some numbers related to uncertainty because we can study the distribution of the model error using the observations from the Fence experiment. These uncertainty results are therefore valid for the special case of the shelter on a vertical plane behind a solid fence only.

We construct histograms of the error of the speed-up from the model (WAsP-shelter) and the observations for each vertical level and downstream position for all the full-scans within the interval \( \theta \leq 0 \pm 75^\circ \), i.e. 1408 samples. Two of these are illustrated in Fig. 49, each corresponding to a particular position in the scanning grid of the WS system. As shown, the error distributes close to a Gaussian distribution; at positions close to the fence and the ground the distribution becomes bimodal (not shown) because of the limits artificially imposed to the model predictions (see Fig. 46).

From these histograms, we can least-squares fit a Gaussian distribution and from it estimate the mean and the standard deviation of the error. The behavior of the mean of the error in the speed-up (or the model ‘bias’ for predicting the speed-up) for all vertical levels as function of the downstream distance is illustrated in Fig. 50, where we see a similar behavior as that for the normalized error in Fig. 47; the further from the ground, the lower the model bias. For vertical
levels below the fence height, the bias in the speed-up up can reach a value of 1, i.e. a 100% relative error.

The behavior of the standard deviation of the error in the speed-up (the model ‘spread’, also sometimes called ‘uncertainty’, for predicting the speed-up) for all vertical levels as function of the downstream distance is illustrated in Fig. 51. The plot shows that, except for \( z/h \leq 0.46 \) when \( 3 \leq x/h \leq 4 \), the spread of the error in the speed-up is generally \( \leq 0.4 \) for all vertical levels and downstream positions, and reduces the further from the fence.
Figure 40: Speed-up $\text{sign}(u) \frac{U(z)}{U_o(z)}$ on the vertical plane behind the fence for each vertical level (frames) for case I (see text in Sect. 7.3 for the explanation of the line types)
Figure 41: Similar to Fig. 40 but for case II
Figure 42: Similar to Fig. 40 but for case III
Figure 43: Similar to Fig. 40 but for case IV
Figure 44: Similar to Fig. 40 but for case V
Figure 45: Similar to Fig. 40 but for case VI
Figure 46: Ensemble-averaged modeled (solid lines) and observed (markers) speed-up on each vertical level as function of the downstream distance from the fence

Figure 47: Normalized error (markers) between the modeled and the observed ensemble-averaged wind speed on each vertical level as function of the downstream distance from the fence. In solid lines the corresponding fit to the error (see text for details)
Figure 48: Shelter (half of it) estimated at each vertical level as function of the downstream distance from the fence based on WAsP-shelter

Figure 49: Distribution of the error $\varepsilon$ in the modeled and observed speed-up for the Fence experiment for two positions on the vertical plane. The grey histograms show the distribution of the error on each full-scan, the solid line a Gaussian fit to the histogram, the vertical solid line shows the mean of the error and the dashed lines show the standard deviation of the Gaussian fit
Figure 50: Mean of the error in the speed-up predicted by WAsP-shelter on each vertical level as function of the downstream distance from the fence based on the Fence experiment.

Figure 51: Standard deviation of the error in the speed-up predicted by WAsP-shelter on each vertical level as function of the downstream distance from the fence based on the Fence experiment.
8 Summary and conclusions

In this report, we provide first an overview of a number of analytical solutions for the shelter behind obstacles, which are available in the literature, namely the 2D infinite fence model of Perera (1981) and the 3D (but 2D-based) models of Taylor and Salmon (1993) (WEMOD) and WAsP (WAsP-shelter), and describe their main characteristics and differences. Similarly, we describe the main characteristics of a RANS-based model we have available at DTU for performing CFD simulations.

Secondly, we present intercomparison and evaluation of the different models with shelter-like observations and cases found in the literature; we find good agreement between the result of the analytical solutions and between the results of the analytical solution and wind-tunnel-based porous 2D fence, particularly for WEMOD within the far wake region \( (x/h \gtrsim 6) \). For the wind-tunnel solid cube cases, the analytical models generally perform well in the far-wake and for \( z/h \gtrsim 1 \), and large differences can be found outside these regions; from the number of CFD simulations available, the trend is to improve the shelter predictions within the regions where the analytical models have large disagreements with the wind-tunnel studies.

Thirdly, we test the sensitivity of the models to e.g. roughness length and angular resolution; neither WAsP-shelter nor WEMOD are found to be largely sensitive to these two parameters. However, the results from the models, in particular those from the CFD simulations, are very sensitive to the way we post-process them in order to reflect the behavior of the observations. Taking into account the distribution of the direction within the interval of directions, normally selected for model evaluation, can have a strong effect on the model results compared to the result of using only the simulation at the center of the direction interval. Further, taking into account the variability of the wind direction, within the time period where the observation is taken, when post-processing the model results can have an important effect on the predicted shelter.

Fourthly, we describe the Fence experiment that we conducted at Risø using the WindScanner infrastructure. This experiment was performed with the aim to create a database of shelter measurements and a set of flow cases that can be used to evaluate obstacle models, their accuracy and uncertainty. Three synchronized lidars measured the shelter behind the fence on a vertical plane and a mast was deployed for deriving the inflow conditions. We define six cases based on the relative direction of the inflow to the fence and we observe lower shelter effects for larger relative directions. For some cases, the shelter is observed within the whole vertical plane, which extends up to \( z/h \approx 2 \) and \( x/h \approx 11 \). Velocity profiles observed in the far wake converge onto each other using self-preserving forms from two-dimensional wake analysis.

Finally, we perform evaluation of the obstacle models using the shelter measurements from the Fence experiment. Generally, the CFD simulation results taking into account the distribution of the direction within the direction interval provide the most accurate results compared to those only using the CFD simulation correspondent to the direction at the center of the interval and also compared to WEMOD and WAsP-shelter (for these two latter cases this is observed for the near-wake region). In the far-wake, both WEMOD and WAsP-shelter are in good agreement with the observations for all vertical levels on the plane. Looking at the results of WAsP-shelter, in particular, we find that in the far-wake and for all vertical levels, the relative model error decreases with downstream distance and height and is below 20%. A fairly good estimate of the error seems to be a percentage of the shelter itself. We also find that the error distributes close to Gaussian, and that for the far-wake the mean of the error in the speed-up is less than 0.4 (also decreasing with downstream distance and with height) and the speed-up uncertainty is lower than 0.4.
References


