WIND TURBINE WAKE INTERACTIONS; RESULTS FROM BLIND TESTS

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Abstract. Results from three "Blind test" Workshops on wind turbine wake modeling are presented. While the first "Blind test" (BT1, 2011) consisted of a single model turbine located in a large wind tunnel, the complexity was increased for each new test in order to see how various models performed. Thus the next "Blind test" (BT2, 2012) had two turbines mounted in-line. This is a crucial test for models intended to predict turbine performances in a wind farm. In the last "Blind test" (BT3, 2013) the two turbines were again mounted in-line, but offset sideways so that the rotor of the downstream turbine only intersected half the wake from the upstream turbine. This case produces high dynamic loads and strong asymmetry in the wake.

For each "Blind test" the turbine geometry and wind tunnel environment was specified and the participants were asked to predict the turbine performances, as well as the wake development to five diameters downstream of the second turbine. For the first two tests axisymmetry could be assumed if the influence of the towers was neglected. This was not possible in BT3 and therefore only fully 3D methods could be applied. In all tests the prediction scatter was surprisingly high.

1. Background
The NREL full scale wind tunnel tests, completed in 2000, and the following blind tests by a large number of calculation methods (Simms et al. [1]) demonstrated how important it is to have detailed data to validate predictions against. The comparison showed that there was large uncertainty in the prediction methods, which called for more refined computer codes. Discussions of some of the issues that surfaced after the tests was presented in the special issue of Wind Energy, which was published in 2002 (Schreck [2]).

Since the NREL tests, significant improvements in turbine performance and wake development prediction methods have emerged. The progress in wake predictions over a decade of research may e.g. be found by comparing the review papers by Crespo et al. [3] and Sanderse et al. [4]. From simple analytical wake models based on classical theories, the standard is now to solve transport equations for turbulence properties or solving the turbulent field in time and space using large eddy simulation. But even at these levels of sophistication the results obtained rely heavily on assumptions incorporated by the modeler. This was clearly demonstrated in the comparisons of wake predictions performed by Cabezón et al. [5] using various turbulence transport equation models.

Many wake model studies have used full scale turbine wake data for validation. The disadvantages with this procedure is that the amount of data is sparse and initial and boundary conditions are not known in sufficient detail to allow one-on-one simulations to be made. In this respect wind tunnel studies are preferable, since the flow conditions may be specified at all
levels required to set up a proper simulation. The major drawback is that the models operate at much lower Reynolds numbers than found at full scale. As part of the joint Norwegian research programs denoted Nowitech and Norcowe it was decided to set up a model experiment to be used as a data source when testing out turbulence models or developing new tools. Together Nowitech and Norcowe are involved in research on most aspects of offshore wind turbine technology and have about 35 PhD or PostDoc members, many involved with wind turbine aerodynamics. Before the data was released it was deemed a good idea to arrange open blind tests to find how the current models used would perform if only the turbine geometry was known.

The wind turbine model used for these tests was designed with the specific aim to form a test case for prediction methods. Therefore this is not a typical wind turbine layout, since measurement and wind tunnel restrictions, combined with test case challenges, had to be considered. For a test case it was important to use a simple geometry while also introducing effects that might be difficult to handle by a prediction method. This led to the design shown in figure 1. As may be seen from the photo, the turbine has 3 blades and the rotor sits on top of a stepped tower consisting of four cylinders of different diameters. The nacelle is also circular with a diameter of \( d = 90 \text{mm} \). It has an almost semi spherical hub cover at the front and back.

The model was tested in a wind tunnel that has a test section which is almost 12m long. The height is about 2m and the width almost 3m. For details, see one of the references, Adaramola & Krogstad [6] or Krogstad & Adaramola [7]. The rotor diameter is \( D = 0.894 \text{m} \) and the centre of the rotor is located \( z = 0.817 \text{m} \) above the floor level.

The model was designed to operate at 10m/s with a tip speed ratio of \( \text{TSR} = 6 \), which is typical for a full scale turbine. In order to test the Reynolds number dependence of the blades, the performance of the turbine was measured over a wide tip speed range for reference velocities ranging from about \( U_{\text{ref}} = 7 \) to 15m/s. The power and thrust coefficients were found to be independent of Reynolds numbers for \( U_{\text{ref}} > 9 \text{m/s} \) (see e.g. Krogstad & Adaramola [7]).

1.1. The blade geometry
To make the blade specification simple, the same airfoil was used all along the span. The airfoil selected is the 14% thick NREL S826 airfoil. It is originally intended to be used near the tip of
a full scale turbine. The blades were made of aluminum and the maximum load on each blade was estimated to be about 15N. It was assumed that the blades had sufficient stiffness so that geometrical changes due to the loads could be neglected. Therefore this slender airfoil could be used also for the root sections. The airfoil is shown in figure 2.

![Figure 2. Shape of the NREL S628 airfoil](image)

2. The BT1 test case

In this first "Blind test" the case consisted of the single model turbine shown in figure 1. Except for the geometry specifications and wind tunnel inlet conditions, no further information was given by the organizers. Thus, if the participants needed e.g. lookup tables to determine the load distributions on the blades, they would have to generate this information themselves. The way this was obtained would have impact on the results. Hence, the first compulsory output was predictions of the power and thrust coefficients for tip speed ratios (TSR) from TSR = 1 to 12. (The runaway TSR had been measured to be about TSR ≈ 11.5.)

The main focus of the blind test was however on the wake development behind the turbine. The participants were therefore asked to provide profiles of the velocity defect, \((U_{\text{ref}} - U)/U_{\text{ref}}\), and turbulent kinetic energy, \(k^2/U_{\text{ref}}^2 = \frac{1}{2}(u_x^2 + u_y^2 + u_z^2)/U_{\text{ref}}^2\) at three downstream positions, \(x/D = 1, 3\) and 5, measured from the plane of the rotor. The data should be provided for three operating conditions, TSR = 3, 6 and 10, i.e. in the fully stalled region, at design conditions and near the runaway point. The predictions were compared with measured thrust forces, power coefficients as well as velocity profiles. Full details of the measurements and predictions for BT1 may be found in Krogstad and Eriksen[8].

2.1. Participants and methods

Calculations were submitted by eight groups, some of whom supplied multiple predictions, giving a total of eleven submissions. In order to start the wake calculations, the power and the thrust coefficients of the turbine must first be estimated. Except for two groups, this data was obtained using a Blade Element Momentum method. Three simulations resolved the flow down to the level of the boundary layer on the blade and thereby avoiding the assumptions implied in the BEM methods. Below is a list of participants and the essence of their methods.

2.1.1. Agder Energy Production

J. A. Lund of Agder Energy Production used the software openFoam in combination with the \(k - \omega\) SST turbulence model to calculate the wake flow. The rotor was modeled by means of an actuator disk where \(C_P\) and \(C_T\) were taken from a BEM model. It was documented that
the numerical setup was grid-independent. The results will be labelled Lund \( k - \omega \) SST in the plots.

2.1.2. Acona Flow Technology

E. Manger of Acona Flow Technology was the only participant who modeled the wind tunnel test case as it was performed. The entire model, including the rotor, tower and nacelle, located in the test section was meshed using \( \times 10^6 \) cells. A sliding mesh was used to allow the blades to rotate. The flow was solved using the Ansys Fluent v.13-0 software and the \( k - \omega \) SST turbulence model was incorporated in the solution. The results will be referred to as Manger \( k - \omega \) SST.

J. Kvalvik of the same company performed a simulation using openFoam. Kvalvik used a cylindrical rotating grid containing the three rotor blades which was freely suspended in a short square box (about 2.5 diameters long) without the inclusion of the nacelle or tower. The turbulence model used was the one-equation model of Spalart and Allmaras and grid independence was demonstrated using up to \( \times 10^6 \) cells. Because the computational domain was relatively short, no wake data were submitted. The label used for these data is Kvalvik.

2.1.3. CMR Prototech

CMR Prototech submitted data, performed by T. Hansen, for a simulation that resolved the full flow details down to \( y^+ \approx 1 \) on the actual blade geometry. The software package used was STAR CCM+ and the turbulence was modeled using the \( k - \omega \) SST turbulence model. Hansen assumed axisymmetry and therefore did not include the tower. Only one blade sitting on the hub was modeled and periodic boundaries were applied to include the effects of the other blades. A grid refinement test with up to \( \times 10^6 \) cells was performed to demonstrate grid independence. His predictions will be denoted as Hansen \( k - \omega \) SST.

2.1.4. DTU Mechanical Engineering

J. N. Sørensen and R.F. Mikkelsen at DTU, Denmark, did in principle provide 3 sets of simulation data, although two of these are closely related. The simplest was a BEM method for a turbine in an unbounded flow field (labelled Sørensen & Mikkelsen BEM-nocorr). The model size is in the upper range of what may be considered a free field operation. Sørensen & Mikkelsen had therefore also estimated appropriate corrections for \( C_P \) and \( C_T \) due to the blockage caused by introducing a drag force in the tunnel. Thus the correction depends on the estimated \( C_T \) and at high thrust values corrections up to about 10% were made to the estimated free field \( C_T \). The label used for these data is Sørensen & Mikkelsen BEM-wtcorr.

Finally the group delivered data for a combined actuator line / Large Eddy Simulation (LES) using a program called EllipSys3D. The forces on the flow as generated by the rotor were represented by rotating actuator lines and the rest of the flow was resolved using the Navier-Stokes equations on a very fine mesh. Only the sub-grid turbulence is modeled while the large scale turbulence is predicted directly from the Navier-Stokes equations. Hence, this solution would normally be considered very accurate, but the accuracy in the wake also depends on the modeling of the rotor loads from the BEM methods. Their predictions are labelled Sørensen & Mikkelsen LES.

2.1.5. GexCon

The GexCon group, consisting of J.A. Melheim, L. Sælen and M. Khalil, performed calculations using the software package FLACS – Wind which is developed by GexCon. This is a transient CFD solver which in this case used the standard \( k - \epsilon \) turbulence model. The computational domain was similar to the wind tunnel dimensions, but the increase in tunnel
height to compensate for the growth of side wall boundary layers was not included. The rotor was represented as an actuator disk and the disk data was obtained using a BEM method. The effects of the tower were not included in the simulations. These predictions have been denoted Melheim et al. $k - \epsilon$.

### 2.1.6. National Institute of Advanced Industrial Science and Technology, Japan

T. Kono from National Institute of Advanced Industrial Science and Technology, Japan, supplied the second set of data generated using LES with a software package called Front Flow/red. The rotor was simulated as an actuator disk where the data was taken from a conventional BEM simulation. The simulations were performed in a domain representing the wind tunnel test section and the effects of the tower and the nacelle were included by adding body forces. $2.4 \times 10^6$ cells were used. His data is labelled Kono LES.

### 2.1.7. NTNU

Data was submitted from the Department of Civil and Transport Engineering, NTNU, by L. Suja and P. Thomassen. The performance of the wind turbine was predicted using the aero-elastic code called ASHES, which makes use of the BEM theory. The method predicts $C_P$ and $C_T$, as well as the radial distribution of the blade loadings, but is not able to provide information about the wake development. The results from this group will be labelled Suja & Thomassen BEM.

### 2.1.8. StormGeo / Univ. Stavanger

These simulations were submitted by S. Kalvig. She has used the software openFoam and represented the rotor as an actuator disk. $C_P$ and $C_T$ data for the disk was obtained from the measurements reported in Krogstad et al. [9]. The calculations were performed in a domain corresponding to the test section of the wind tunnel using a standard $k - \epsilon$ method, but the effects of the tower were not included. The predictions have been denoted Kalvig $k - \epsilon$.

### Table 1. BT1 model overview

| Name                        | Model type                     |
|-----------------------------|--------------------------------|
| Hansen                      | $k - \omega$ SST / FR / SST     |
| Manger                      | $k - \omega$ SST / FR / SST     |
| Kvalvik                     | $k - \omega$ SST / FR / IEq     |
| Kono LES                    | BEM-AD / LES                   |
| Sørensen & Mikkelsen LES    | BEM-AL / LES                   |
| Kalvig                      | BEM-AD / kEps                  |
| Melheim et al. $k - \epsilon$ | BEM-AD / kEps               |
| Lund $k - \omega$ SST       | BEM-AD / SST                   |
| Sørensen & Mikkelsen BEM-nocorr | BEM-No tunnel walls / no wake calculations |
| Sørensen & Mikkelsen BEM-wtcor | BEM-With tunnel walls / no wake calculations |
| Suja & Thomassen BEM        | BEM / no wake calculations     |

### 2.2. BT1 model overview

The methods described above may be grouped according to the models used for the rotors and the equations included to solve turbulence field (see table 1). BEM implies that the blade loads are determined by a Blade Element Momentum method and tables of lift and drag coefficients,
AD means the rotor is approximated by an Actuator Disk, while AL is used for an Actuator Line model. FR means that a CFD code has been used to resolve the flow down to the rotor surface. The turbulence models have been denoted SST, $k\epsilon$ and $1Eq$ for the $k-\omega$ SST, $k-\epsilon$ and Spalart-Allmaras models, respectively. LES means that the wake is resolved using Large Eddy Simulations.

3. BT1 Results

3.1. Predicted performance

The power coefficient is shown in figure 3(a) and the thrust coefficient in 3(b). The symbols used are the same in all figures with measurements presented as the large black dots to distinguish them from the predictions. The predictions by the Hansen $k-\omega$ SST, Kvalvik Spalart-Allmaras and Manger $k-\omega$ SST methods are also represented by filled symbols to highlight the methods that solve the flow over the blades in detail, instead of relying in the BEM methods.

![Figure 3. Turbine performance. (a) Power coefficient, (b) Thrust coefficient.](image-url)

The spread in the power predictions (figure 3(a)) is surprisingly large, considering that most of the predictions use the same Blade Element Momentum theory as the basis. The turbine peak performance is generally predicted to within $\pm 10\%$ and most methods predict the peak performance where it should be, around the design tip speed ratio of TSR=6.

For the very low TSRs, where the blades are deeply stalled, the deviation from the measured power coefficient, $C_P$, is mostly small, while at very high TSRs there is significant spread in the predictions. Previous studies (Krogstad and Lund[10]) have shown that the first signs of stall occur around TSR=4 and it was therefore expected that the principal signs of departure from the measurements would be found here. But except for the predictions by Kvalvik, none of the methods appear to have special problems here. As the stall deepens, however, (at TSR=3 the blades are fully stalled) the spread becomes larger. But for the deep stall region for TSR < 3, all methods behave well. This suggests that the predictions of the airfoil data, that has to be performed before a BEM calculation can be made, have been successful for most participants, possibly with some inaccuracies in the transition region from the first signs of stall until the profile is completely stalled.

Looking at the thrust coefficient (figure 3(b)), it is seen that the general trend is that $C_T$ is under-predicted by all models. There is considerable disagreement about its value for high TSR. This does not appear to have a systematic trend with respect to prediction methods in the sense that the BEM and CFD methods both appear to be distributed over the entire range...
of predicted values. It should also be noted that while the Sørensen & Mikkelsen BEM-nocorr method predicts the lowest $C_T$ values for $TSR > 5$, this cannot be because it does not include the restrictions caused by the wind tunnel walls. The Suja & Thomassen BEM method, which also assumes infinite flow domain, is one of the best performers for $TSR$ higher than the design condition.

The fully resolved simulations of the Kvalvik Spalart-Allmaras method perform excellent over the entire range of operations, which is remarkable since the computational domain is terminated only 2D downstream of the rotor and the predicted $C_P$ was not particularly good. The predictions of Hansen $k – \omega$ SST, Kvalvik Spalart-Allmaras and Manger $k – \omega$ SST are in close agreement over the full range of $TSR$, with Kvalvik performing slightly better. At high $TSR$ the Manger $k – \omega$ SST method performs slightly better than the one by Hansen $k – \omega$ SST in predicting $C_T$, suggesting that the latter method slightly under-predicts the airfoil performance at low angles of attack. Since the Hansen $k – \omega$ SST simulations use about five times as many grid points as Manger $k – \omega$ SST, and the turbulence model used is the same, this may suggest that Manger has been more successful in distributing the points wisely.

3.2. Wake data

The participants were asked to provide predictions of the spatial distribution across the wake at zero angle of yaw for three positions downstream of the rotor plane, at $X/D = 1, 3$ and $5$, for three operating conditions, $TSR = 3, 6$ and $10$. Space does not allow the results for all stations and all parameters to be shown here, so we restrict the presentation to the mean velocity and turbulent kinetic energy distributed along a horizontal line across the wake at the rotor axis elevation for the design condition, $TSR=6$, which should be the simplest case.

The first station for which data was requested was at $X/D=1$ (figure 4(a)). Here $X$ is the distance measured from the plane of the rotor. The velocity defect measurements show an asymmetry in the form of a peak around $y/R \approx 0.2$. They are also present in the predictions of the two methods that include the full tower and nacelle geometry (Kono LES and Manger $k – \omega$ SST), although to a much smaller extent, and are therefore assumed to be due to the wake behind the tower. All predictions show the same shape with a dip in the centre. This is partly due to the flow acceleration caused by the displacement effect of the nacelle and partly because the nacelle was omitted in many methods, so there is no energy extraction here.

It is interesting to observe that the STAR CCM+ predictions by Hansen, using the $k – \omega$ SST turbulence model, produce almost identical results to the LES predictions at this station. And

Figure 4. Mean velocity profiles along a horizontal line for $TSR=6$. (a) $X/D = 1$, (b) $X/D = 5$. 
so does the predictions by Lund $k - \omega$ SST, who uses a different solver but the same turbulence model. In fact these methods give a better collapse with the LES of Sørensen & Mikkelsen than the LES of Kono does.

The same comments that were made for $X/D = 1$ basically apply to the wake profiles at the last measurement station, $X/D = 5$ (figure 4(b)). (This is outside the calculation domain for the LES of Sørensen & Mikkelsen, so no results are available here.) The measurements have now started to develop a stronger velocity defect on the left hand side than on the right side. It is believed that this is a footprint of the tower wake which slowly rotates in the opposite direction to the rotor motion. This asymmetry is also to some extent captured by the predictions made by Manger $k - \omega$ SST and by Kono LES that incorporated the tower in the computational domain.

3.2.1. Turbulent kinetic energy profiles at TSR=6

The normalized turbulent kinetic energy at $X/D = 1$ along the horizontal line is shown in figure 5(a). (Note that the ordinate axis is logarithmic here since the range of the energy across the span is large and because the various prediction methods estimate quite different turbulence levels.) The turbulent kinetic energy distribution is characterized by strong peaks generated by the tip vortices from the blades. These peaks are captured by the predictions of Melheim et al. $k - \epsilon$, Kalvig $k - \epsilon$, Lund $k - \omega$ SST, and by Sørensen & Mikkelsen LES, although the levels are one order of magnitude lower than in the measurements. It is surprising that the LES of Kono did not pick up these peaks very well and gave so different turbulent energy from the LES predictions of Sørensen & Mikkelsen along the outer half of the wake. The profiles of Hansen $k - \omega$ SST have the correct shape, but the peak near the tip is more than two orders of magnitude too low. The measurements also indicate a high turbulence level behind the hub which could only be captured by the predictions where the hub of the model was included.

Figure 5(b) show the distributions at $X/D = 5$. Surprisingly, the simple actuator disk / $k - \epsilon$ model of Kalvig is now performing very well as it gives the right shape as well as roughly the correct level. The predictions by Manger $k - \omega$ SST also show the correct shape, although the turbulent kinetic energy level is low. But the method of Melheim et al. $k - \epsilon$ is the one that appears to represent the measurements the best. The other methods, which all predict roughly the same $k$ levels, show very ragged distributions, indicating that the spanwise turbulent diffusion is underestimated.

It is hard to select a best method or turbulence model from the presented wake and turbulence distributions due to the large variations in the results. But most predictions are at least able
to predict the general shape of the velocity defect profiles as well as the location of the tip vortices and how they grow downstream. Overall it appears that the LES method of Sørensen & Mikkelsen (which also produced good predictions at \( X/D = 3 \), not shown here) is producing the most consistent results, but this comes at considerable computational costs.

4. The BT2 test case
The overall impressions from the first ”Blind test” was that many of the methods were predicting the flow around a single wind turbine quite well. There was a demand for a more challenging case and so in 2012 a second ”Blind test” was organised. This time two similar turbines were mounted in line so that the downstream turbine operated entirely within the wake of the first. The two turbines used identical blades, so except for a small difference in nacelle diameters, the two rotors were identical. But the first test had shown the importance of the tower wake, as it affected the wake symmetry, so a bulkier tower was used on the upstream turbine. Again it should be pointed out that the purpose of these blind tests was to generate test cases for prediction methods and not to simulate state of the art turbine designs.

![Figure 6. Blind test 2 setup](image)

The setup of BT2 is shown in figure 6. The upstream turbine \( T_1 \) was positioned \( 2D \) from the test section inlet. It was verified that this location is sufficiently far downstream for the operation of the turbines not to affect the uniformity of the inlet velocity profile. The rotor of downstream turbine \( T_2 \) was positioned \( S = 3D \) downstream from the upstream turbine rotor. Both turbines rotate the same way and had the same hub height. The turbines were alternately positioned on a high accuracy six component aerodynamic balance in order to allow the thrust on the rotor to be measured separately. The thrust of the tower and nacelle was measured and subtracted from the thrust of the turbine, to yield the thrust of the rotor alone. Each turbine was fitted with a torque transducer and a speed of rotation sensor on the shaft mounted directly behind the rotor. The power generated by both turbines could be measured simultaneously. The measurement and predictions for BT2 are fully documented in Pierella et al.[11].

Again the invitation document for the ”Blind test 2” workshop included all the geometrical details of the turbines, and the inlet conditions, but nothing more. The task given was to predict the performances of both turbines and the wake development downstream of \( T_2 \). Obviously this gave a handicap for modelers who had not been entirely successful in predicting the wake behind the first turbine in BT1, but the philosophy was that now that the wake data behind the upstream turbine had been made available they could improve their predictions.
Three test cases were defined. For all three the upstream turbine was operated at its design condition (TSR = 6). In Case A the downstream turbine was operated at TSR = 4 (close to its peak performance), Case B had TSR = 7 for the downstream turbine (close to runaway) and for Case C TSR was 2.5 (rotor operating in the stall mode). For both turbines the upstream reference velocity was used for scaling.

4.1. Participants and methods at BT2
There were eight participants at BT1 and the number was the same for BT2, except that there was a few of the BT1 groups dropping out and a few new coming in.

Manger from Acona participated with the same CFD model as last time (see 2.1.2 above for details).

Khalil and Sælen of GexCon again participated with their FLACS—Wind method (described in section 2.1.5 above) and produced two sets of predictions. One was for the turbines in the wind tunnel test section where the walls were treated as no-slip boundaries. This will be labeled GexCon-sim1. In the other set of data the walls were removed and the simulation emulates an unbounded domain. This will be denoted GexCon-sim2.

Mikkelsen and Sarmast from DTU and KTH delivered LES predictions (section 2.1.4 above).

The wind turbine group of Agder Energy Production (section 2.1.1) had in the meantime been reorganized into a company called Meventus, but the method used was the same. Therefore the label used in the next set of plots has been changed to Meventus.

The new participants and their methods were as follows:

4.1.1. CMR Instrumentation
Hallanger and Sand of CMR Instrumentation used an in-house CFD code called Music. The code was developed at CMR, and uses a standard steady state $k-\epsilon$ model for turbulence closure with the coefficients proposed by Launder and Spalding[12].

The discretized equations are solved on a co-located grid using the SIMPLE algorithm from Ferziger and Peric[13]. The rotors were modeled by an actuator disc with rotation, where the 2D airfoil data were estimated using XFOIL (see Drela[14]). A sub-grid turbulence model is added, in order to represent the additional turbulence generation by the wind turbine, adapted from models for flow in large rod bundles by Sha and Launder[15]. The total number of grid points for the case was $3.9 \times 10^6$. The walls were included in the simulations, while the towers of the turbines were not. The hubs were taken into account as a flow resistance, but the axial extent of the nacelles was not represented.

The results from Hallanger and Sand will be labeled CMR.

4.1.2. de Vaal - NTNU Marintek
De Vaal performed his calculations using Fluent v. 14.0. Axisymmetry was assumed, and the turbine actuator disc was included via a BEM model. The 2D airfoil data were calculated using the Q3quick software implemented by García[16], and used the experimental airfoil performance data set that had been generated the DTU contributors since the previous ”Blind test”. The grid was composed of 508 $\times$ 236 cells in the streamwise and radial directions, respectively. 80 of the radial cells were used along the rotor span. The tower and the nacelle were not simulated, but the wind tunnel walls were taken into account as no-slip surfaces. The turbulence closure model was the Reynolds Stress model (RSM), as implemented in Fluent.

These simulations are denoted DeVaal.

4.1.3. University of Puerto Rico
Leonardi and Martinez Tossas, from the University of Puerto Rico, used OpenFOAM to perform a LES simulation with a standard Smagorinsky sub-grid scale model ($C_S = 0.1$). The
turbine rotors were simulated as actuator lines. The walls, roof and floors were included in the simulation as no-slip surfaces, while the towers and the nacelles of the turbines were omitted. High Reynolds number airfoil data from Somers[17] were used as input for the simulations, and the AirfoilPrep tool from NREL [18] was used to correct the airfoil data for rotational effects.

The results from University of Puerto Rico will be labeled Leonardi.

4.1.4. Middle East Technical University, METU, Turkey

The results from METU were produced by Uzol and Sezer Uzol. The authors used the free-wake code AeroSIM+, a 3D unsteady free-wake vortex panel method. For the turbines, the blades are discretized using quadrilateral panel elements and vortex ring elements are placed within each element. During an unsteady run, at each time instant, the influence coefficients of surface and wake panels are calculated using the induced velocity values from each vortex segment on the collocation points by means of the Biot-Savart law. Then the blades are moved and a new solution is calculated for the next time step. No tower or hub were modeled, while the boundaries of the wind tunnel were treated as no-slip surfaces.

The results from METU will be labeled Uzol.

4.2. BT2 model overview

The methods, grouped according to the models used for the rotors, and the equations applied to solve turbulence field are listed in table 2.

| Name         | Model type          |
|--------------|---------------------|
| Acona        | FR / SST            |
| Meventus     | FR / SST            |
| CMR          | BEM-AD / kEps       |
| De Vaal      | BEM-AD / RSM        |
| GexCon-sim1  | BEM-AD-With tunnel walls / kEps |
| GexCon-sim2  | BEM-AD-No tunnel walls / kEps |
| DTU-KTH      | BEM-AL / LES        |
| Leonardi     | BEM-AL / LES        |
| Uzol         | Vortex Panel Method |

5. BT2 Results

5.1. Predicted performance

In the following plots, the marker symbols used are indicative of the rotor modelling techniques: a square means that the rotor was fully resolved, a triangle is used when the rotor was modeled as an actuator disc and a circle when an actuator line model was used. The vortex panel method of Uzol is different from all the others and is indicated by a five pointed star.

The mandatory predictions for the upstream turbine at its design condition (TSR = 6) show a surprisingly large scatter (±20%) in the power coefficient (see Figure 7(a)). It was not expected because the results from BT1 were closer to the measurements and the data had been available for a year so an improvement rather than a worsening was expected. Also experiments at the correct Reynolds numbers had been performed on 2D versions of the airfoil both at DTU, Denmark, and METU, Turkey. However, some participants preferred to provide their own data sets using software such as XFOIL.
When the same airfoil data sets were used in different BEM models, as in the case of de Vaal and DTU-KTH, the predicted values varied significantly, suggesting that the predictions depend just as much on how the data was implemented as on the quality of the data. In this case de Vaal used an actuator disk model while DTU-KTH used the actuator line model. Judging from the predicted power coefficients, the more complicated actuator line method appear to give better estimates than the actuator disk. Acona’s predictions, the only one this time to resolve the flow down through the boundary layers to the rotor surface and including the turbine structure, performed quite well, as also found in the BT1 blind test.

Figure 7(b) shows a similar scatter for the thrust coefficients. The free vortex method of Uzol gave far too high thrust, while all the other models either matched or underpredicted the rotor thrust compared to the measurements. Acona’s results again gave the best agreement. The actuator disc predictions from de Vaal and CMR matched closely the thrust of the rotor. It was less successful in the power prediction, suggesting that the airfoil performance data they used are very different. All the actuator line methods had a tendency to underpredict the thrust, similarly to what happened in the Blind Test 1. The GexCon-2 simulation, which did not include the walls, show lower power and thrust values than the one with walls (GexCon-sim1), indicating a significant effect of the solid blockage on the rotor performance.

The power coefficients predicted for $T_2$ (Figure 7(a)) show more scatter than for $T_1$. The downstream turbine had its peak efficiency at $\lambda_2 = 4$ (Case A), while in Case B, at $\lambda_2 = 7$, the turbine was close to the runaway point. In Case C ($\lambda_2 = 2.5$) the power produced by the turbine was significantly lower than at the optimum point, and the blades were most likely heavily stalled. Despite the low incoming velocity and the consequent low local Reynolds number experienced by $T_2$, the experimental performance curve of $T_2$ does not indicate any of the irregularities observed at low Reynolds numbers for the single turbine. The downstream turbine was probably less sensitive to Reynolds number effects now due to the high turbulence level in the wake of the upstream turbine.
Except for the predictions of de Vaal, all the simulations correctly predicted the peak performance at $\lambda_2 \approx 4$. At $\lambda_2 = 4$, GexCon-sim1 performed best, closely matching the experimental results, while the simulation without the walls (GexCon-sim2) predicted a significantly lower performance. The fully resolved simulation from Acona performed well, overestimating only marginally the power production. Despite using the same 2D airfoil data, DTU-KTH and de Vaal had again different power results, with the actuator line model being lower and more accurate. This result is remarkable, since a higher thrust prediction for the first turbine means less kinetic energy available to the second turbine, and in this sense the prediction from DTU-KTH should have been higher than the ones from de Vaal. This suggests that de Vaal’s model overestimated the turbulent diffusion in the wake and hence the velocity recovery rate. The free wake method from Uzol dramatically overestimated the downstream turbine power production, as it did for the upstream turbine.

The thrust coefficients for $T_2$, Figure 7(b), are mostly under-predicted, but closer to the experimental data for low TSRs. The CMR method performs very well throughout the whole tip speed range, being in close agreement with the experiments. Again the Acona model produced high quality predictions under all conditions, while the other models showed high variability and sensitivity to the operating conditions of the turbines.

For discussions of the $\lambda = 2.5$ and 7 cases, please see Pierella et al. [11] for full details.

5.2. BT2 wake data

The fact that the upstream turbine has its peak performance at TSR $\approx 6$ and the downstream turbine at TSR $\approx 4$, suggests that since the rotors are identical the effective wake velocity across the rotor area seen by $T_2$ is about 67% of the incoming velocity, $U_{ref}$. However, in order to avoid any uncertainties due to an interpreted reference velocity for $T_2$, it was decided to scale all data with the same upstream velocity, $U_{ref}$.

5.2.1. Mean velocity profiles at TSR=6 for $T_1$ and 4 for $T_2.$

Here we show the mean velocity profiles at $X = 1D$ and $X = 4D$ for Case A, when both turbines were operating at their peak performance. For the other cases the reader is referred to Pierella et al. [11] where all cases are documented. The experimental mean velocity profile at $X = 1D$ (black dots in figure 8(a)) was slightly asymmetric, primarily due to the wake generated by the tower of the second turbine. The velocity outside of the wake was 20% higher than the reference velocity due to the blockage effect of the turbines, which produces an overall drag coefficient of about 1.2. Therefore, the modellers who underestimated the thrust for both turbines, like Meventus, predicted a lower velocity increase outside of the wake. Furthermore, not including the walls in the simulation also led to a deviation in the prediction of the undisturbed velocity, as demonstrated by the 10% difference between GexCon-1 and GexCon-2. At the centre line the models that did not include the nacelle failed spectacularly by producing only minor velocity defects or even a speedup in the centre region. Thus only the predictions by Acona and CMR reproduced the velocity profile shape here.

At $X = 4D$ turbulent diffusion has smoothed out the details of the initial conditions, which has improved the agreement between the predictions and the measurements (figure 8(b)), even in the cases where the turbine geometry have not been faithfully represented. The asymmetry from the first station has been shifted due to the wake rotation so that the traces of the tower has moved over from the negative $Z$ to the positive $Z$ side. The wake covers almost the whole wind tunnel width and the profile has a nearly Gaussian shape. The method of CMR performed very well across the whole span, while Acona’s predictions indicated still a very strong velocity defect near the centre of the wake, suggesting an underestimation of the turbulent diffusion. This was confirmed by low turbulence levels predicted at all downstream distances (see next section).
While the LES method of DTU-KTH predicted the wake very well across most of the span, the LES from Leonardi and the RANS-RSM from de Vaal performed quite well in the outer part of the wake and in the shear layer, but the velocity peak at the centre line was still over 100% too high, again suggesting that the spanwise diffusion was strongly underestimated. The free wake code from Uzol appears to have had convergence problems going from $X = 4D$, predicting a rather noisy profile at $X = 4D$ which was narrower than at $X = 1D$.

5.2.2. Turbulent kinetic energy profiles at TSR=6 for $T_1$ and 4 for $T_2$.

The profiles of the streamwise normal Reynolds stress, $u'^2$, at the same stations are shown in figures 9(a) and (b). Only $u'^2$ was measured using a single wire hot wire probe. Many of the simulations resolved the Reynolds stress tensor, but for those who used $k$ transport equations the isotropic approximation $u'^2 = 2k/3$ has been used in the presentations.

Close to the rotor ($X = 1D$), the experimental streamwise Reynolds stress profile, figure 9(a), features three distinct peaks, two in the outer wake shear layer and one close to the wake centre line, slightly skewed to the positive side of the $Z$ axis. The two outer peaks are characteristic of the tip vortices while the centre peak comes from the nacelle and the tower wakes and is therefore asymmetric. While the scatter in the predictions for BT1 was so large that logarithmic ordinate axes had to be used, all the models predicted a turbulence intensity of the same order of magnitude as in the measurements for this case. The LES from DTU-KTH is seen to have produced oscillations at this position. This is particularly evident near the centre, where strong turbulence has been generated in the shear layer produced by the centre line velocity overshoot. The tip vortices in the Acona simulations also produced two stress peaks but the level is much too low. It was suggested by the author that this may be related to problems in the interpolation of the turbulent kinetic energy at the interface between the revolving rotor mesh and the background grid. However, there are obvious problems also away from the interface. The method did not predict the peak at the wake centre line observed.
Most of the methods predicted too high turbulence intensity in the tip vortex region at this first position. However, this changed rapidly as the flow developed downstream, so that at the last station \((X = 4D)\) about half of the methods strongly underestimated the stress levels (figure 9(b)). Here turbulent diffusion has spread a considerably amount of turbulent energy across the wake both in the predictions and measurements and so the profile shape is virtually identical for all methods, but the peak levels are significantly different. All the 2-equations models are now predicting too low turbulence intensities, which seems to confirm that such turbulence models are too dissipative to correctly represent a complicated anisotropic turbulent flow. The actuator line LES from DTU-KTH and RSM from de Vaal agree quite well with the experimental data all across the wake. They employed the same airfoil data for their rotor predictions, but incorporated totally different descriptions of the turbulent transport process.

6. The BT3 test case

In the last "Blind test", organised in 2013, the same two turbines from BT2 were used, but they were offset from the centre line by about \(D/4\) either way so that the downstream turbine rotor only intersected half the wake of the first turbine. This is probably a more realistic operating condition for turbines in a wind farm and constitutes additional challenges compared to the BT2 case. The second rotor now experiences a highly non-uniform inflow with velocities that change rapidly around the periphery. This adds important hysteresis effects on the flow over the blades which may make the steady state data bases for the blade characteristics questionable. Also it introduces serious dynamic forces on the blades, but these could not be measured in the present setup.

Again the focus of the test was on the performance of the downstream turbine and the wake generated behind it. While the first two "Blind tests" had been for turbines exposed to...
Figure 10. Upstream turbine and grid used in BT3.

a uniform, low turbulence inflow conditions, an additional case was generated for this "Blind test", where a background turbulence level typical for atmospheric conditions were generated using a large scale grid. Figure 10 shows the grid upstream of turbine $T_1$. The turbulence field generated by this grid has been extensively documented, see e.g. Davidson and Krogstad[19]. At the position of the upstream turbine rotor the flow is uniform and the turbulence level was $T_u = 10\%$, decaying to about 5% at the location of the second turbine rotor plane.

6.1. Participants and methods at BT3

Due to the increased complexity of this "Blind test" and because axisymmetry could no longer be assumed even in the simplest modelling, the number of participants for this test dropped to 5. Acona, DTU-KTH, GexCon and CMR contributed predictions with the same methods applied in BT2. New contributions were submitted by CD-adapco. Their details are as follows:

6.1.1. CD-adapco.
S. Evans from CD-adapco, London, UK, provided predictions using their own software Star-CCM+. Around the rotors, cylindrical domains were created so that the arbitrary sliding interface functionality of STAR-CCM+ could be used to model the rotor motion. A polyhedral mesh was created containing 14 million mesh elements with the boundary layer on the blades being resolved down to a $Y^+$ value of less than 2, somewhat dependent on the operating conditions. Predictions were provided using the $k – \omega$ SST Detached Eddy Simulation (DES) model with curvature corrections. The mesh was created in such a way that the DES model operated in LES mode in the wake regions of the flow. The simulation ran in a two-step approach. First the case was run using a steady approach with multiple rotating frames. After the simulation was considered to be sufficiently initialised, it was switched to transient simulation. For a description of how the software is used for rotating flows, see Medonca et al.
6.2. BT3 model overview

The solution methods for the rotors and the turbulence equations used for BT3 are listed in table 3.

| Name      | Model type     |
|-----------|----------------|
| Acona     | FR / k-ω-SST   |
| CD-adapco | FR / k-ω-DES   |
| CMR       | BEM-AD / kEps  |
| GexCon    | BEM-AD / kEps  |
| DTU-KTH   | BEM-AL / LES   |

7. BT3 Results

Due to space limitations and to allow comparisons with BT2, only the non-grid case will be presented here. For full documentation the reader should refer to Krogstad et al.[21].

7.1. Predicted performance

As in the BT2 cases, the operating conditions for $T_1$ was kept constant at a tip speed ratio of TSR = 6. The speed of rotation for $T_2$ was then varied in order to cover the required TSR range.

![Figure 11. Turbine performances, Case A, no turbulence grid. (a) Power coefficient, (b) Thrust coefficient.](image-url)

The scatter in the power predictions for the upstream turbine is about the same as in the two previous "Blind tests". This is surprisingly large, considering that most of the participants have already preformed predictions for these turbines a couple of times before and know the performance curves. Compared to the BT2 test case, the energy output of $T_2$ has now almost doubled and is stretched out over a much broader TSR operating range. It may be noted that for TSR < 3, the $T_2$ power production follows the same trend independent of the amount of wake it operates in. This is because the blades are completely stalled and the time needed to recover from the stall appears not to be sufficient as it passes in and out of the wake. Since the
lift and drag coefficients are virtually independent of angle of attack in the fully stalled region, the operating condition is not essential for the amount of energy produced.

The predictions for the second turbine vary by more than 50% in some regions, but this is understandable, since we here have the most complicated test case so far. However, some of the predictions for $T_2$ are in fact very good at high tip speeds, e.g. the curves obtained by CMR Instrumentation and CD-adapco for TSR $> 6$. The $T_2$ power predictions by DTU are excellent for the entire TSR range. An oddity in the $C_P$ predictions is that the only two methods that fully resolve the flow over the blades all the way down through the boundary layers (i.e. Acona and CD-adapco) produce so dramatically different results for TSR $< 9$.

Thrust coefficient measurements (figure 11(b)) show that except for a short region around TSR $= 4$, the $C_T$ data for both turbines are very similar. Intuitively the velocity fields seen by the two rotors are expected to be very different with the downstream turbine being exposed to a lower momentum. Despite this, the coefficients are the same when scaled with the same parameters, showing that the physical forces are in fact almost identical. It is conjectured that the velocity increase seen by $T_2$ in the external flow outside the wake from $T_1$ may have been sufficient to compensate for the momentum loss in the wake, to produce very similar turbine drag. The general trend is that $C_T$ is mainly over-predicted for the $T_1$ turbine, but under-predicted for $T_2$. GexCon has matched the force on turbine $T_1$ very well, but underpredicts the forces on $T_2$ significantly at TSR $= 8$. The differences between the Acona and CD-adapco predictions are again quite evident, especially for TSR $< 6$ where the Acona model is doing very well.

7.2. Wake data

As an example of the wake complexity behind the second turbine and the predictions obtained, the data for TSR$_1 = 6$ and TSR$_2 = 4.75$ will be presented. These are the conditions when both turbines operate at their peak performances. Results for the other cases (TSR$_1 = 6$ and TSR$_2 = 3.5$ and 8) may be found in Krogstad et al.[21].

7.2.1. Mean velocity profiles at TSR=6 for $T_1$ and 4 for $T_2$.

The first station for which data was requested was at $X/D=1$ downstream of the rotor plane of $T_2$. The mean velocity profiles measured along a horizontal line parallel to the floor at the elevation of the rotor axis are shown in figure 12(a), for the non-turbulent case. Also, data was requested for $X/D=3$ and these are shown in figure 12(b). The centre of turbine $T_1$ is located at $y/R = -0.45$ and the rotor extends from $y/R = -1.50$ to $y/R = +0.61$. $T_2$ has its centre at $y/R = +0.45$ with a rotor that spans from $y/R = -0.55$ to $y/R = +1.45$. These are indicated by the arrows above each plot to help the interpretation of the data. The outer edges of the combined wake are quite evident, but the central part is a mix of influences from the two wakes.

Compared to the wake behind a single turbine operating at its best performance, this is a much more complicated wake and very far from the Gaussian profiles used by simple models. However, the sharp gradients are quickly smeared out by diffusion so that the profile at $X/D=3$ is already much smoother.

Except for the CMR $k-\epsilon$ model, all methods have reproduced the general shape of the profile at $X/D = 1$ (figure 12(a)). The GexCon method performs very well, avoiding the oscillations found in the predictions of Acona, CD-adapco and to some extent in the DTU results. As the flow develops downstream the strong gradients disappear in all models except in the predictions by Acona. This model predicted a profile shape at $X/D = 3$ (figure 12(b)) which is very similar to the one at $X/D = 1$, suggesting too low turbulent diffusion. Again, the GexCon model was very close to the measurements, while the diffusion in the $k - \epsilon$ model of CMR is definitely too strong, making the profile almost Gaussian here. In general the other methods predict too strong velocity defects at this station.
7.2.2. $< u_2^2 >$ stress profiles at TSR$_1 = 6$ and TSR$_2 = 4.75$.

The streamwise normal Reynolds stresses are shown in figure 13(a) for $X/D = 1$ and in figure 13(b) for $X/D = 3$. Again the simplification $< u_2^2 > \approx 2k/3$ was used for the $k$ models. For this "Blind test" all Reynolds stresses were measured at a few stations and the excellent performance of the simplification was documented (see Krogstad et al.\cite{21} for details).

The complexity of the wake is very evident in the stress profiles. Very distinct energy peaks in the many tip vortices may be observed. All but the CMR method have predicted these peaks and perhaps not surprisingly the LES methods have done so most successfully. The turbulence level generated by the Acona method is very low at both stations suggesting that the kinetic energy generation from the shear layers has been underestimated. This supports the conjecture that the very small change in mean velocity profiles between the two stations was due to incorrect turbulence prediction.

The turbulence introduced by the grid significantly affected the wake data (not shown here). Partly by making the incoming wake smoother and partly by increasing the diffusion in the
second wake and thereby removing many of the steep gradients. Together these had a significant effect on both the mean velocity and kinetic energy profiles.

8. Concluding remarks
The performance of model turbines and the wake formed by the rotors have been predicted for three test cases of increasing complexity. The methods comprised all levels of sophistication that are being used today, ranging from simple standard Blade Element Momentum methods to Large Eddy Simulations.

In most studies reported in the literature, where the aim is to sort out the best turbulence model to be used, the same operator uses the same program and grid distribution while incorporating different models in an attempt to best reproduce a reference distribution. This could be experimental results or other reliable references. Blind tests like those reported here take away the target and therefore opens up for the uncertainty connected with the model operator. This is more like the environment a design engineer works in. Using the code available he/she tries to set up the calculation to the best of his/her skills. This, of course, makes it difficult to objectively sort out a best prediction method but gives valuable information about the state of the art of the computations that are routinely made for wind turbines.

The spread in the results was probably larger than was initially expected. The uncertainty in the predicted turbine performance is of the order of ±10% near the design conditions for the simplest case of a single turbine in a uniform flow, but increases considerably when it was operating in the wake of another. Especially when only part of the wake hits the rotor.

To compute the wake flow, standard $k-\epsilon$ models, $k-\omega$ SST models and even large eddy simulations were used. There is no obvious winner when it comes to the turbulence model used. There is as much variation within the groups using the $k-\omega$ SST model as there is between these and the other models applied, underlining the dependence of the skill of the model developer or user on the results. Unfortunately the picture was not much clearer with the LES simulations either. However, it appears safe to say that using actuator line theory to predict the initial rotor condition gives better wake predictions than the actuator disk. In general this gave results that were more in line with the experimental data.

Wind tunnel size limited the downstream distance that the wakes could be measured to about 5D for the single turbine and 3 to 4D for the two turbine cases. It would have been interesting to see how the methods would perform down to, say $X/D = 10$, since it appears that some of the methods have problems accounting for the spanwise turbulent diffusion and therefore retain spanwise inhomogeneity over much longer distances than are indicated in the measurements and the LES calculations.

It is apparent from this exercise that when it comes to wind farm planning, the estimates of wake development has not reached the reliability that is necessary for accurate estimates of turbine interactions. However, the situation may not be as bad as some of the tests reported here may suggest. Most of the tests were performed in homogeneous and virtually turbulence free conditions. It was found that when adding free stream turbulence the agreement between measurements and predictions improved. In shear flow conditions the differences may be even smaller since both shear and background turbulence tend to increase turbulence diffusion, making the wakes more Gaussian.

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