Invitation to the 2012 "Blind test 2" Workshop Calculations for two wind turbines in line

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Abstract

As part of the activities on wind turbine technology organized by NOWITECH / NORCOWE we would like to invite you to participate in a so-called "Blind test 2" workshop to be held in Trondheim in October 2012.

The first "Blind Test" workshop (BT1) was held in Bergen, October 2011, where 9 groups of scientists delivered performance and wake development predictions for a model turbine that had been extensively tested at NTNU. This provided very useful information about the state of the art of wind turbine prediction methods. As a follow up we now invite you to participate in the somewhat more complicated "Blind test 2" workshop (BT2), where the performance and wake development for two similar turbines operating in line is to be predicted.

The organizers of the workshop will provide the geometry of the two turbines which are used in the test. The two turbines have been individually extensively tested. For the workshop configuration, the turbines are arranged in line, separated by 3 rotor diameters, and their performance characteristics has been measured in the large wind tunnel of the Dept. Energy and Process Engineering, NTNU. The wake properties has also been measured at three distances downstream.

Given the geometric information of the turbines, research groups who have a suitable computer code are invited to compute the performance of the turbines for a set of predefined operating conditions. The output from the predictions will be compared with the experimental data obtained by the organizers. The participants will then come together at a workshop in Trondheim, scheduled for October 2012, to discuss the results and try to sort out discrepancies between simulations and experimental data. We will also focus on the lessons learned from BT1 and BT2 and hopefully be able to provide recommendations for improved predictions and what will be useful new experimental information.

The results may be published in a suitable journal afterwards.

1 Test case definitions

In the following we provide information about how to set up the test case. Depending on whether your computational model assumes axisymmetric flow and uses a rotating frame of reference or computes a rotating rotor in a fixed environment, you may want to use the exact tunnel dimensions or convert the cross section to an equivalent circular cylinder in order to account for possible blockage effects and wall boundary layers .

We provide full details of the model geometry. A CAD file of the two turbines, with dimensions and geometrical shape, will be available for download. Details about the airfoil (NREL s826), the chord length and twist distributions are available in tables if you would rather generate your own geometry input. You may also download a CAD file that describes one blade mounted on one third of the nacelle of turbine T_2. The choice depends on your computational code and personal preferences. In any case the information needed is described in the following sections.

1.1 The models

A picture of the models in the wind tunnel is shown in Figure 1. Both turbines have three bladed upstream rotors, with the same blade geometry, but a slightly different rotor diameter, due to some differences in nacelle diameters. The blades were machined in aluminum and have a NREL s826 airfoil section from root to tip.

Figure 1: Model in the wind tunnel

Fgure 2 gives the dimensions of the two turbines and shows that the models have slightly different tower and nacelle layouts. Also note that the tower heights show their physical dimensions to the fixing points and not the actual height as operated in the wind tunnel. These heights will be specified further down. The turbine operated upstream will in the following be referred to as T_1, while T_2 will be the downstream one. The two turbines are positioned at a streamwise separation of $3D$, where D is defined as 89.4 cm, which is the diameter of the rotor of the downstream turbine T_2.

The tower of turbine T_1 is a cylinder with a constant diameter of 11 cm, while for T_2 the rotor sits on top of a stepped tower consisting of 4 cylinders of different diameters.

This is the same turbine that was used in BT1. The nacelle of turbine T_1 is a circular cylinder of $D_{T_1}^{nac} = 13\ cm$ diameter. The nacelle of T_2 is also circular but with a diameter of $D_{T_2}^{nac} = 9\ cm$. The rotor diameter of T_1 is therefore $D_{T_1} = 94.4\ cm$, while $D_{T_2} = 89.4\ cm$. Both turbines are driven by a belt transmission connected to a $0.37\ kW$ asynchronous motor, controlled by a Micromaster 440 Siemens frequency converter. Turbine T_1 has the belt mounted inside the tower, while for T_2 the tower is too slender to allow this, so the belt runs behind the turbine tower.

Turbine T_2 has an almost semi spherical hub cover at the front. Its deviation from a sphere is small but if the exact geometry is deemed necessary, it may be obtained from the organizers as a table in an Excel file. In the CAD file mentioned above, the correct shape is of course included. At the rear, the cap is again formed from a sphere, slightly offset and with a somewhat larger diameter, as indicated in the figure.

Turbine T_1 has a slightly pointed hub cover. The dimensions are documented in Figure 2; a CAD file and an excel file are also available for download for this turbine.

1.2 The blade geometry

The blades use the NREL S826 airfoil along the entire span. The normalized coordinates for the profile are given in Section 2. We also include a table of chord length and twist angle as function of the radius, which you will find in Section 3. Combined, this information allows you to define the blade geometry.

For your convenience, we supply a CAD file containing a 120 degrees segment of the nacelle of turbine T_2 with one blade mounted in the correct position. We also supply the 3D files of both complete turbines.

The CAD files may be downloaded from
http://www.ivt.ntnu.no/ept/downloads/workshop2012.
The login details are:
User: Workshop2012
Password: TurbinS826

1.3 The test environment

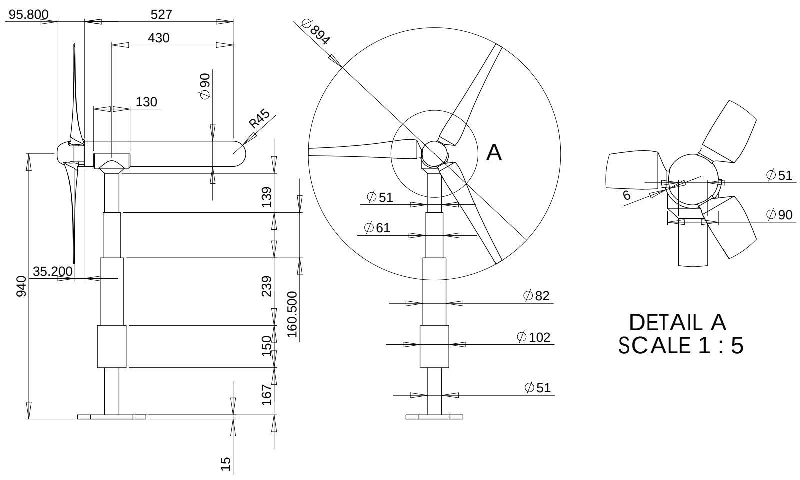
The model turbines were tested in a wind tunnel which has a test section which is 2.71m wide and is 11.14m long. The tunnel has a flexible roof which has been adjusted for zero pressure gradient at a bulk tunnel speed of $U \approx 14$m/s. The tunnel heights are given in table 1.

Table 1: Height of test section as function of distance from the inlet

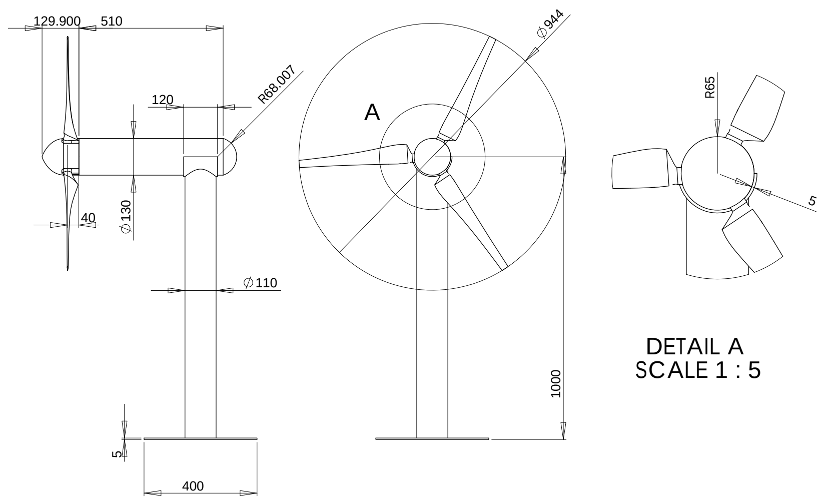
X (m)	Height (m)
0.000	1.801
2.810	1.801
5.621	1.813
8.435	1.842
11.150	1.851

At the inlet to the test section the flow is uniform across the cross section to within $\pm 1\%$ and the turbulence intensity has been measured to be 0.3%. Over the area swept by the rotor, the inlet flow is uniform to within $\pm 0.5\%$

Both turbines have been mounted at the spanwise center line in the wind tunnel, while the center of the nacelles are $0.817\ m$ from the floor (see figure 2). The rotor plane of T_1 is located $2D$ from the test section entrance.



(a) Downstream Turbine, T_2



(b) Upstream Turbine, T_1

Figure 2: T_1 and T_2, tower and nacelle dimensions

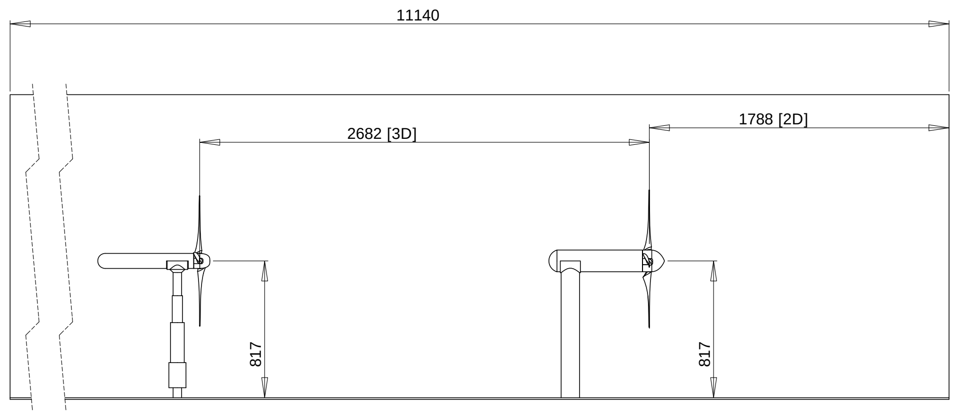


Figure 3: Wind tunnel placement of the turbines

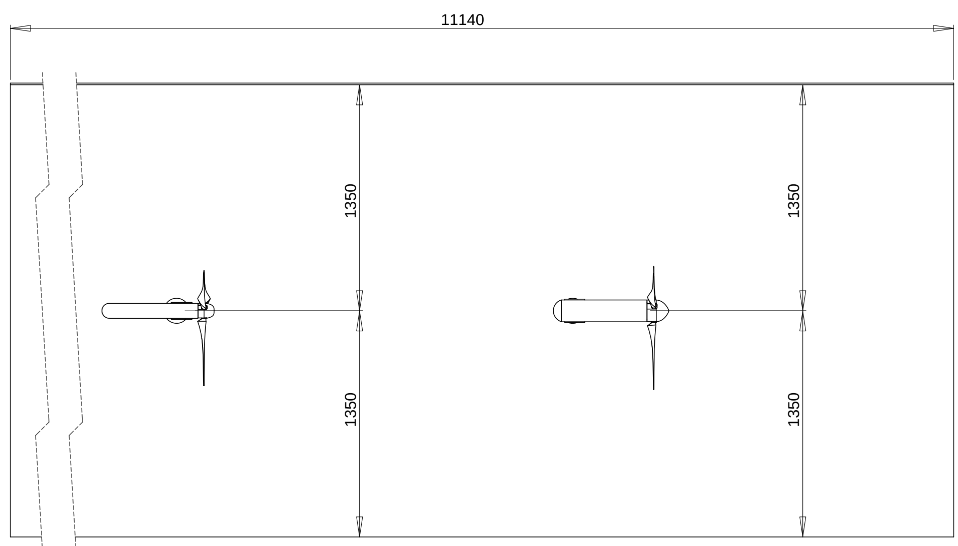
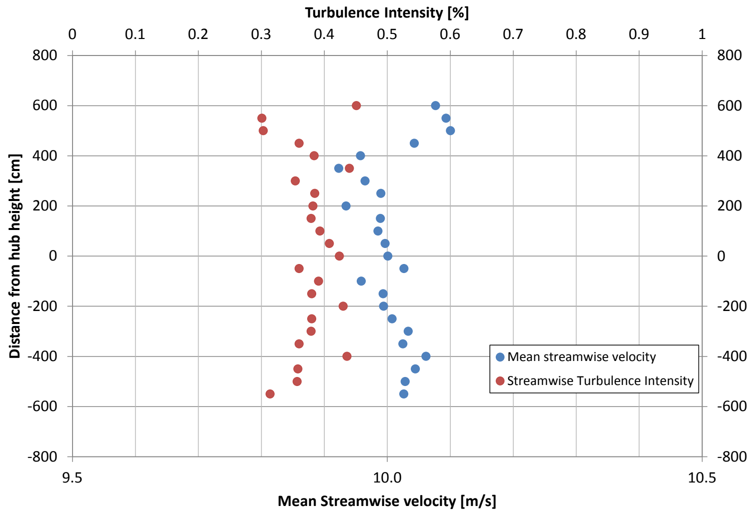


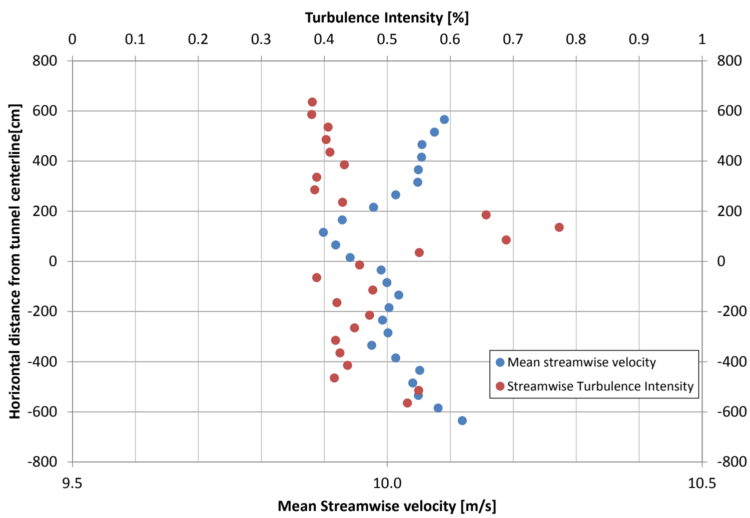
Figure 4: Wind tunnel test section seen from above

Measurements show that in this arrangement the presence of the operating turbine has a negligible influence (less than 1%) on the velocity profile at the inlet of the wind tunnel test section, independent of the turbine rotational speeds.

The presence of the rotating turbine will undoubtedly influence the average speed in the tunnel by inducing a variable pressure drop in the test section, depending on the rotational speed. The bulk velocity of the wind tunnel, which is the velocity calculated from the pressure drop across the wind tunnel contraction (the contraction ratio being 1:4.36), has been monitored and kept constant throughout the whole experiment.



(a) vertical profile



(b) horizontal profile

Figure 5: Velocity profiles at the upstream turbine position, 2D from the inlet section

At the chosen bulk velocity set point, the average velocity across the turbine rotor is equal to $U_\infty = 10.0\ m/s$ at $2D$ downstream from the inlet section, where the upstream turbine is placed.

The temperature is also monitored to take into account air density variations due to temperature changes.

In figure 5 we show the vertical and horizontal velocity profiles measured with of the empty wind tunnel $2D$ downstream from inlet of the test section inlet, where the upstream turbine is placed.

The velocity profile is constant to within ±1% over the area swept by the rotor with a small dip near the tunnel centre line.

2 Definition coordinates for NREL S826

The definitions of the NREL airfoil used for the blade may be found in Somers [1] and is shown in Figure 6. Table 2 contains a list of the normalized coordinates for the airfoil. Somers specifies the geometry, as well as estimated performance characteristics, such as lift and drag coefficients, for a range of full scale operating Reynolds numbers. If you are using a Blade Element Momentum or Actuator Line calculation method, you may need to generate data for the actual operational Re of the model turbine. You can do this e.g. by using the program package called $XFOIL$, see Drela [2].

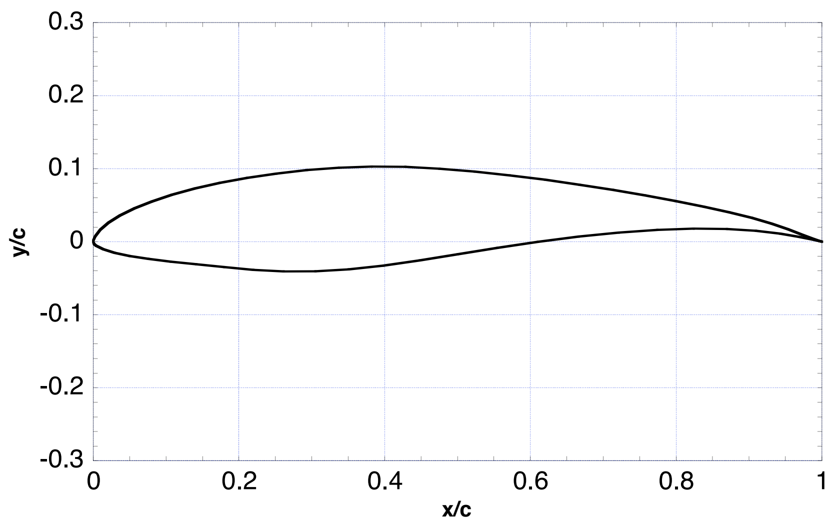


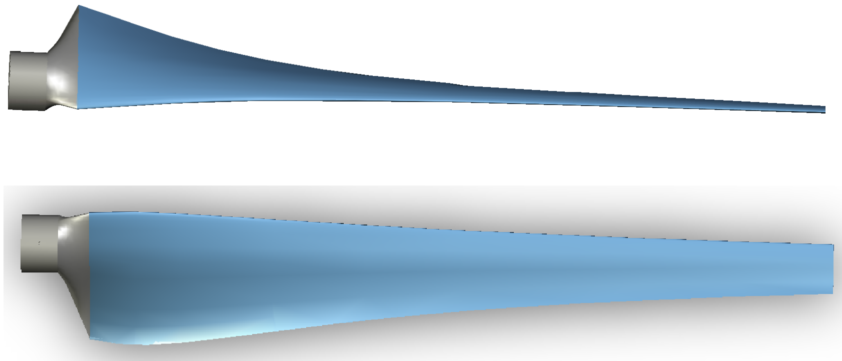
Figure 6: Shape of the NREL S628 airfoil

3 Chord and Twist data

Table 3 contains a list of the airfoil chord length and twist angle as function of the radius. (The twist angle is measured with respect to the rotor plane.) Please note that for the first 3 coordinate sets the geometry consists of a circular cylinder used to fix the blade to the hub. Therefore a major part of this section is located inside the hub when defining the rotor geometry. This section has been identified in the table by setting the twist angle to 120 degrees. Between the last circular section and the first NREL profile a linear transition region has been added to give a smooth change of shape. The blade is shown in Figure 7(a) and 7(b).

Table 2: Coordinates for the NREL S826 airfoil

x/c	y/c (upper surface)	x/c	y/c (lower surface)
0.0000	0.0000	0.0000	0.0000
0.00018000	0.0015900	0.00021000	-0.0014600
0.0025500	0.0074800	0.00093000	-0.0027400
0.0095400	0.016380	0.0021600	-0.0040300
0.020880	0.025960	0.0036700	-0.0052500
0.036510	0.035800	0.013670	-0.010350
0.056360	0.045620	0.029200	-0.015180
0.080260	0.055190	0.049980	-0.019600
0.10801	0.064340	0.075800	-0.023620
0.13934	0.072880	0.10637	-0.027290
0.17395	0.080680	0.14133	-0.030910
0.21146	0.087580	0.17965	-0.034860
0.25149	0.093430	0.21987	-0.038550
0.29361	0.098070	0.26153	-0.040640
0.33736	0.10133	0.30497	-0.040510
0.38228	0.10294	0.35027	-0.037940
0.42820	0.10249	0.39779	-0.032800
0.47526	0.10005	0.44785	-0.025630
0.52324	0.096070	0.50032	-0.017200
0.57161	0.090940	0.55484	-0.0084100
0.61980	0.084890	0.61055	-0.0001500
0.66724	0.078160	0.66644	0.0069900
0.71333	0.070950	0.72142	0.012540
0.75749	0.063410	0.77434	0.016210
0.79915	0.055720	0.82409	0.017840
0.83778	0.047980	0.86953	0.017410
0.87287	0.040290	0.90945	0.014980
0.90391	0.032620	0.94257	0.011130
0.93072	0.024790	0.96813	0.0068900
0.95355	0.016950	0.98604	0.0032400
0.97251	0.0098200	0.99655	0.0008400
0.98719	0.0043100	1.0000	0.0000
0.99668	0.0010300		
1.0000	0.0000		



(a)

(b)

Figure 7: Blade a) seen in the plane of rotation and b) in the axial direction.

Table 3: Definitions of chord length and twist angle as function of blade radius.

r (m)	c (m)	ϕ (deg)
0.0075000	0.013500	120.00
0.022500	0.013500	120.00
0.049000	0.013500	120.00
0.055000	0.049500	38.000
0.067500	0.081433	37.055
0.082500	0.080111	32.544
0.097500	0.077012	28.677
0.11250	0.073126	25.262
0.12750	0.069008	22.430
0.14250	0.064952	19.988
0.15750	0.061102	18.034
0.17250	0.057520	16.349
0.18750	0.054223	14.663
0.20250	0.051204	13.067
0.21750	0.048447	11.829
0.23250	0.045931	10.753
0.24750	0.043632	9.8177
0.26250	0.041529	8.8827
0.27750	0.039601	7.9877
0.29250	0.037831	7.2527
0.30750	0.036201	6.5650
0.32250	0.034697	5.9187
0.33750	0.033306	5.3045
0.35250	0.032017	4.7185
0.36750	0.030819	4.1316
0.38250	0.029704	3.5439
0.39750	0.028664	2.9433
0.41250	0.027691	2.2185
0.42750	0.026780	1.0970
0.44250	0.025926	-0.7167

4 Operating Conditions

This test consists of three operating configurations for which the computational output are requested. For all set-ups the downstream separation of the turbines will be $3D$, or $\Delta x = 268.2\ cm$, and the blade pitch angle will be $\beta = 0$.

4.1 Test case A

In case A, the upstream turbine (T_1) is operated at its design condition:

$$\lambda = \Omega R / U_{ref} = 6. \tag{1}$$

The downstream turbine T_2 is operated at a TSR which will be close to the maximum power output in the wake condition, $\lambda = 4$. Both TSR are here referred to the reference velocity seen by the upstream turbine.

4.2 Test case B

In case B, the upstream turbine will still be operated at the optimum TSR of $\lambda = 6$ but the downstream turbine runs at a TSR higher than the optimum one. This was chosen to be $\lambda = 7$.

4.3 Test case C

The upstream turbine will still be operated at the optimum TSR of $\lambda = 6$ but the downstream turbine is now operating at a TSR which is lower than the optimum. $\lambda = 2.5$ in this case.

5 Computation output

We expect calculations from various groups using a range of prediction methods. Some may want to use Actuator Disk or Actuator Line theories and some will use full three-dimensional CFD methods. It will not be possible to use Blade Element Theory since the hypothesis of constant inflow velocity will fail for the second turbine. We expect the amount of output that may be generated will depend very much on the method applied. We have therefore specified different types of output to be generated. The "Mandatory output" specified in Section 5.1 is considered a minimum to be able to participate. It consists of the overall performance of the two turbines and the wake characteristics for setup A (see section 4).

Even though your method may be capable of predicting the power and thrust coefficients correctly, there is no guarantee that it has reproduced the flow field and load distributions on the blades satisfactorily. To find out more about this, we ask for some extra output about the blade load distributions, if your method is capable of supplying this.

5.1 Mandatory output

The operating conditions for the turbines should be set to a free stream velocity of $U_{ref} = 10.0\ m/s$ and air density of $\rho = 1.2\text{kg/m}^3$. The same reference velocity should be used for both turbines when scaling the output, even though the downstream turbine will experience a different mean velocity than the first due to the presence of the upstream turbine.

As specified earlier, the design tip speed ratio for both T_1 and T_2 was $\lambda = \Omega R / U_{ref} = 6$. This will give a Reynolds number at the design point of $Re_c = \lambda U_{ref} c_{tip} / \nu = 103600$, where c_{tip} is the tip chord length and ν is the kinematic viscosity of air.

All participants are required to provide the following output for Test case A:

1. The power coefficient, $C_P = \frac{2P}{\rho U_{ref}^3 A}$, where P is the power extracted from the wind and A is the rotor swept area ($A = \pi D^2/4$), calculated both for the upstream and downstream turbines.

2. The thrust coefficients, $C_T = \frac{2T}{\rho U_{ref}^2 A}$, where T is the force acting on the rotorplane in the direction of the wind (the forces on the turbine towers and nacelles has to be subtracted from the thrust).

3. The three non-dimensional mean velocites, U/U_{ref}, V/U_{ref} and W/U_{ref}, along a horizontal and a vertical diagonal through the wake centre at positions $X/D = 1$, 2.5 and 4 from the downstream turbine rotor.

4. The streamwise turbulence intensity, $I = \frac{u'_{rms}}{U_{ref}}$, along a horizontal and a vertical diagonal through the wake centre at positions $X/D = 1$, 2.5 and 4 from the downstream turbine rotor, where u'_{rms} is the root mean square of the turbulent streamwise velocity fluctuation and U_{ref} is the reference velocity.

5. Documentation that the solution is grid independent.

6. A 2 pages maximum description of the method you are using which gives sufficient information to allow us to classify your method in order to group the results according to methods.

If your method is primarily calculating the wake and use the above data as input, you must specify how you have obtained the data (from a simplified calculation, from colleagues etc.).

5.2 Additional output

The following additional output may also be submitted:

1. The same quantities mentioned in the mandatory output, but at the operating conditions specified in Test cases B and C.

2. No measurements will be available for the following items, but a comparisom between methods is deemed interesting. The following outputs, for both turbines, and for all three setups, are of interest:

   (a) The normalized blade load distribution in the streamwise direction, $C_{Fx}(r) = \oint (C_{pres}\mathbf{n} \cdot \mathbf{i})\, d\,(S/c)$. Here $C_{Fx}(r)$ is the normalized load force, which is a function of the radial position, r/D, c is the local chord length at radius r, C_{pres} is the pressure coefficient distribution around the blade at a constant r, $\mathbf{n}$ is the unit normal vector of the blade and $\mathbf{i}$ is the unit vector in the streamwise direction. S is the path of integration to be taken around the blade at constant radius. The load distribution should be given from the innermost station of the blade where the airfoil S628 is used ($r = 0.055$m) to the tip.

   (b) The corresponding normalized blade load distribution in the tangential direction, $C_{Fz}(r) = \oint (C_{pres}\mathbf{n} \cdot \mathbf{t})\, d\,(S/c)$. $\mathbf{t}$ is the unit vector in the azimuthal direction. The data should be provided for both turbines in all three setups.

References

[1] Somers, D.M., The S825 and S826 Airfoils. *National Renewable Energy Laboratory* 2005; NREL/SR-500-36344.

[2] Drela, M., Xfoil v. 6.97.
http://web.mit.edu/drela/Public/web/xfoil/

[3] Adaramola, MS Krogstad, P-Å Experimental investigation of wake effects on wind turbine performance *Renewable Energy* 2011, 0960-1481, pag. 2078-2086