The CFD Investigation of Two Non-Aligned Turbines Using Actuator Disk Model and Overset Grids

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Abstract. In this study flow over two axially non-aligned wind turbines is investigated via 3-D CFD analysis by solving Navier-Stokes equations. This setting is the test case geometry for the NTNU’s “Blind-Test” Workshop 3 (BT3) and it aims to predict the performance of the wind turbines and their wake development under asymmetrical flow conditions. The performance of the turbine in the wake of the other turbine is numerically studied for different tip speed ratios. The measurements of velocity profile which is severely disturbed by both turbines are also carried out at the several locations of the wind tunnel. The computational results for NTNU wind turbine test case were obtained by 3-D CFD simulations with two different approaches. The first approach is to employ the actuator disk model, which is used in order to approximate the pressure jump across the rotor disk to simulate the impact of the wind turbines. At the second approach, the actual geometry of the turbine rotor was used, and the rotor blades were rotated using an overset grid methodology over the background grids. The thrust coefficients and the velocity profiles are calculated with two different approaches and the results are compared to experimental data presented in BT3.

1. Introduction

Wind turbines are increasingly being deployed to provide renewable and clean energy. In order to increase their efficiency and reliability, many experimental and numerical studies are performed to explain and estimate the complex and challenging flow field around wind turbines.

As the prominence of wind turbine farms increases, the importance of the wind turbine layouts are becoming a major factor in total energy efficiency. The turbine performances are highly dependent on the incoming wind field, which can be unstable because of atmospheric turbulence, ground boundary layer effects or other physical disturbance such as other wind turbines [2]. Several aerodynamic factors affect the instantaneous blade loads which dominate the turbine performance and lifetime. These aerodynamic sources can be detailed as periodic or non-periodic contributions such as, the wind speed, yaw, wind turbulence, wake dynamics and blade/wake interactions, etc. [3]

To address this complex problem, in 2001 the Unsteady Aerodynamics Experiment (UAE) is performed by the National Renewable Energy Laboratory (NREL) [4]. The gathered data is also compared with numerous studies in the blind test sessions. It has been observed that wind turbine model predictions are including the effects of both the modelling tool and the modeler. The uncertainties of the simulation can be attributed not only to the numerical methods, algorithms or discretization of the problem but also to the turbulence modelling, assumptions and decisions made by the modeler.
There are also sets of wind turbine experiments performed by the NTNU to test the capability of the numerical methods by comparing the results in the blind test workshop sessions. [1, 5 and 6]. These tests investigated the thrust and pressure coefficients of the wind turbines for different tip speed ratios. In addition, the velocity profile of the turbine wake is studied for single turbine and the two turbines aligned and non-aligned cases. The effect of the unsteady wake interaction on the second turbine efficiency and the velocity profiles are investigated.

In this study, “Blind-Test” Workshop 3 (BT3) [1] which is performed by NTNU in December 2013 is numerically investigated by employing actuator disk and overset grid methods. The first approach is to employ the actuator disk model, which is used in order to approximate the pressure jump across the rotor disk to simulate the impact of the wind turbines by using 2-D lift and drag coefficients database for the selected airfoil. Actuator disk model solution is not capable of capturing unsteady flow variations and also the spanwise flow effects on the turbine blades are not considered. Because of those incapabilities of actuator disk model, overset grids method is used to understand the effects of the unsteady flow and the actual blade geometry. As a result, the velocity profiles of the turbine wakes and the thrust coefficients of the turbines are calculated and compared.

2. Methodology
In this study, the flow conditions and the geometry of the wind turbines and tunnel of the BT3 is modeled by using CFD++ software. The workshop provides the detailed geometry of the wind turbines that has been tested in the large wind tunnel of the Dept. Energy and Process Engineering, NTNU in December 2013.

2.1. Geometry of the Wind Turbines
The S826 airfoil is used for the entire span of the wind turbine blade. The geometry and the lift drag coefficients data for S826 airfoil are given in BT3 for the test cases of the wind turbines which are shown in Figure 1.

![Figure 1. Wind turbines geometry positioned in the tunnel.](image)

Both turbines have three bladed upstream rotors, with the same blade geometry but with a small difference in the rotor diameter due to the nacelle geometry. The turbine operated upstream is referred as T1, while T2 is the downstream one. The tower of the T1 is a cylinder with a constant diameter of 0.11 m, while for T2 the rotor is located on top of a stepped tower which has 4 cylinders of different diameters. The nacelle diameter of the T1 is 0.13 m diameter while T2 is 0.09 m. The rotor diameters of the T1 and T2 turbines are 0.944 m and 0.894 m, respectively. The first turbine is positioned 2 diameters and the second turbine is positioned 3 diameters away from the tunnel inlet, where the reference diameter is defined as the second turbine’s rotor diameter which is 0.894 m. The turbine positions are shown in Figure 2 and 3. As seen in Figure 3, with respect to center line, the upstream turbine is offset 0.20 m to the left when seen in the incoming wind direction, while the downstream turbine is offset 0.20 m to right, which gives the total spanwise shift between the two turbines as 0.40 m (~0.45 D).
2.2. The Computational Grids

Two non-aligned wind turbines are modeled by two different approaches: the actuator disks representing the rotors and the overset grids with the actual rotor geometries, which require different types of grid generation due to their numerical procedure. The computational domain size is taken as the same with the wind tunnel size with the length, height and width of the tunnel are defined by x, y, and z coordinates, respectively. Unlike the experimental setup, the height of the tunnel is assumed constant as 1.817 m in the computational domain.

2.2.1. Actuator Disk Model Grid

In this approach, instead of modelling the actual geometry, the upstream and downstream turbine rotors are defined as disks which are created by unstructured domains with 5016 and 3962 2-D triangular cells, respectively. The flow field around the towers and actuator disks are modelled by unstructured tetrahedral cell blocks with the outer boundaries of structured domains which enable to create the outer blocks by structured grids. Overall there are 3 blocks of grids created. The use of the structured outer blocks also allows the boundary layer grid definition near the tunnel walls easily. The computational domain and the grid blocks used with the actuator disks are shown in Figure 4.
2.2.2. Overset Grids

There are five individual blocks of grids created to define two turbine rotors, two turbine towers and the computational domain of the wind tunnel. Because of the complex geometry of the turbine rotors and towers, unstructured grids are used. On the other hand, the tunnel geometry is suitable to use structured grids which enable to control the grid cells’ aspect ratio, size and number precisely. Unlike the actuator disk model, the overset grid model is capable of defining the actual geometry of the rotors. The individual grid blocks and the concatenated flow field grids which define the whole domain are shown in Figure 5 and 6.

![Figure 5. Overset grid blocks of the turbine towers and the computational domain.](image1)

![Figure 6. Overset grids of the 5 overlapped blocks including turbine rotors, towers and the tunnel.](image2)

For the structured/unstructured hybrid grids used, there are several blocks created to define the whole computational grid for two different numerical models. These blocks are defined by different grid types (structured/unstructured) and cell types (tetrahedrals, prisms, pyramids, hexahedrals) and number of cells for each model as given in Table 1. In Table 1, the Block 1, 2 and 3 of the grid with actuator disks stand for the T1 and T2 turbines and the wind tunnel, respectively. For the overset grid, the towers of the first and second turbine are defined as the Block 1 and 2, the rotors are defined as the Block 3 and 4, and finally the wind tunnel corresponds to Block 5.

| Grid with Actuator Disks | Overset Grids |
|--------------------------|---------------|
| Block 1                  | Block 2       | Block 3       | Block 1 | Block 2 | Block 3 | Block 4 | Block 5 |
| Tetrahedrals             | 1081404       | 1185552       | --       | 233899  | 211583  | 560564  | 383325  |
| Prisms                   | 2316          | 4430          | --       | --      | --      | 3804    | 3064    |
| Pyramids                 | 18910         | 24093         | --       | 9924    | 14192   | 22934   | 20058   |
| Hexahedrals              | --            | --            | 1711486  | 5432    | 4480    | --      | 3363750 |
| Total                    | 4028191       | --            | 4837009  | --      | --      | --      | --      |
2.3. Mathematical Modelling
In this study, two different numerical approaches are employed to simulate the flow over the two non-aligned wind turbines. The first approach is the actuator disk model which is a theory describing a mathematical model for an ideal, infinitely thin and homogeneous rotor. The second approach is the use of overset grids which is an effective way to solve complex configuration problems with moving bodies and complex geometries.

2.3.1. Actuator Disk Model
This model is based on the momentum theory for propeller and rotors introduced by Froude [7] and as a continuation of the work of Rankine [8]. The actuator disk concept consists in modelling the rotor as a permeable surface, defined by the rotor swept area on which distribution of forces obtained by the airfoil data and corrected by 3D effects using a blade element approach. In this model, it is assumed that the flow is steady and the effect of the spanwise flow along the blades is neglected. Moreover, the major limitation of this method is the assumption of an infinite number of blades which means that the model is only valid for rotationally symmetric flows [9]. On the other hand, the advantage of the actuator disk model is that it does not require very high computational power and because of the steady-state analysis it is much faster than the sliding mesh or overset grid methods.

In this study, actuator disk model is employed by using CFD++ software which needs several input data in order to mimic the effects of the actual geometry. These inputs can be listed as the number of the blades, the chord and twist of the blade, the rotor radius and hub radius, and the lift and drag coefficients as a function of angle of attack for the airfoils of the blade. In the numerical analysis, steady-state, preconditioned, compressible Navier-Stokes equations are solved. Considering the available computational power and time, realizable k-e turbulence method is employed with wall-function correction model.

2.3.2. Overset Grids:
Overset grids (also known as Chimera grids) is based on decomposing the complex geometry into sub grid blocks which are overlapping each other in the intersection boundaries, which pioneered by Benek et al. [10]. The governing equations are solved independently in each subdomain and the information from one subdomain to another is transferred via specification of interfacial boundary conditions. This can be handled by interpolating all primitive variables from one subdomain to other. However, this may not be enough to provide the globally conservative solution. Conservative solution can be achieved by patching the grids of adjacent subdomains along the common grid surface. To ensure the conservation of mass, momentum and energy, the flux interpolation techniques which are developed by Rai [11], Wright and Shhy[12] are used.

Overset grids provide flexibility to change the geometry and the grid systems locally without changing the regeneration of other grids also enable the relative motion where geometry components or whole bodies move relative to each other. There are mainly three steps in overset grids approach, which are grid generation, hole cutting-blanking and interpolation weighting [13]. In this study, there are five different blocks created for turbine towers, rotors and the wind tunnel individually. After the blocks are concatenated, the cutting and weighting procedure is applied by using CFD++ software. Unlike from the actuator disk model, the overset grid methodology requires unsteady analysis. The unsteady, preconditioned Navier-Stokes equations are solved by using implicit dual-time stepping method [14]. Also, the second order cell-centred finite volume method is used as spatial discretization with multi-grid treatment [15].

3. Results
The 2.71 m wide and 11.14 m long wind tunnel with two non-aligned wind turbines is simulated by using CFD++ software with 10 m/s uniform velocity profile and air density of $\rho=1.2$ kg/m$^3$. In the inlet section, the turbulence intensity is measured 0.24% and the streamwise integral Length scale $L_{uu}$ was calculated as 0.035 m by using the measurements of turbulence kinetic energy and velocity.
fluctuations [1]. The same reference velocity is used for both turbines even though the downstream turbine has been experienced different reference velocity.

The tip speed ratio definition for both T1 and T2 rotors is given as:

$$\lambda = \frac{\Omega R}{U_\infty}$$  \hspace{1cm} (1)

where, $\Omega$ is the angular velocity, $U_\infty$ the freestream velocity and $R$ is the rotor radius.

The CFD simulations are performed for a constant tip speed ratio of 6 for the upstream turbine and for various tip speed ratios of the downstream turbine and the results are compared with the experimental data of the BT3 test case of NTNU [16].

A single time step with 25 inner iterations on 64 AMD 6378 processors running at 2.4 GHz took 250 seconds for overset grid methodology. The simulations are performed for 2000 of time steps resulting in an average run time of 6 days. Note however that the simulations are initialized using a converged solution at a lower tip speed ratio which has been advanced for 3000 time steps. Typically, the actuator disk runs converge in about a day using 64 processors with 2500 iterations. Therefore, using the overset grids is about 6 times more expensive when compared to the actuator disk model.

The overset grids results are obtained by unsteady numerical analysis, therefore it is essential to ensure the solution has been advanced sufficiently in time, in order to obtain meaningful averages of flow quantities. The time-averaged velocity profiles along the horizontal diagonal through of the downstream turbine axis are compared for various time intervals in Figure 7. The time averages are computed after discarding the initial time interval corresponding to 60 revolutions (~3000 time steps) of the upstream turbine.

![Figure 7. The time-averaged velocity profiles along the horizontal diagonal at 1 rotor diameter away from the downstream turbine axis.](image)

In Figure 7, the time-averaged velocity profiles are compared for the case where the downstream turbine has a tip speed ratio of 4.75. The results are almost indistinguishable after 20 revolutions of the upstream turbine (after discarding first 60 revolutions as transient). This can be shown in Table 2 by looking at the L2-norm values of the averages calculated when compared with the results obtained after averaging for 140 revolutions (corresponding to 7 seconds). The L2 error is less than 1% for the averaged solution calculated over 2 seconds, which is acceptable considering the high computational cost involved.
Table 2. Error in L2 norm of the average solutions with respect to 7 sec.

| L2 Norm of Error (%) |       |
|----------------------|-------|
| 1 sec                | 1.39  |
| 2 sec                | 0.66  |
| 3 sec                | 0.34  |
| 7 sec                | 0.00  |

The velocity distributions at several axial locations are presented for both numerical approaches in Figure 8 and 9. The 1st and 4th planes are set to 1 rotor diameter front and behind the upstream turbine. The 2nd, 3rd, 5th and 6th planes are just located front and behind the turbine rotors to observe the pressure and velocity variations due to actuator disk model and overset grids methodology. The 7th and 8th planes are set to 1 and 3 rotor diameters away from the downstream turbine in its wake. The averaged velocity and pressure values are given for each plane in Table 3. The center of the first turbine is set to the coordinates of [0, 0.817, -0.2]. In addition, the flow and kinetic energies (per unit mass) are calculated from these averaged velocity and pressure values and are tabulated in Table 3.

Figure 8. Axial velocity contour cut planes with actuator disk model, TSR=4.75.

Figure 9. Instantaneous axial velocity contour cut planes with overset grids, TSR=4.75.

In Table 3, the velocity, pressure and energy balance values are investigated for each model between the given cut planes. In the actuator disk model, the velocity values are almost the same along the wind tunnel, except small pressure fluctuations between the planes which bound the rotors. This is
due to the actuator disk model which prescribes a pressure difference to simulate the effect of the rotor. On the other hand, in overset grids there exists a pressure difference due to the rotor blades which is accompanied with a decrease in velocity. Since the mechanical energy balance equation (Bernoulli) is valid for steady, incompressible flows with negligible friction, it would not be strictly applicable for overset grids methodology which is unsteady, compressible and with highly active frictional effects due to rotating actual blade geometries. Nevertheless, it is used as a measure of energy conservation through the rotors. The velocity distribution on the previously mentioned cut planes for both numerical methods is shown in Figure 10, on the 7th and 8th cut planes in order to depict the wake downstream of the second turbine.

Table 3. Averaged values on the cut planes shown in Figures 8 and 9.

| Plane # | AD  | OG  | AD  | OG  | AD  | OG  | AD  | OG  | Axial Location |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|----------------|
| 1       | 9.91| 9.66| 99202| 99205| 49.10| 46.69| 82717| 82718| 0 | 0 | -0.894 |
| 2       | 9.90| 9.66| 99201| 99203| 49.05| 46.67| 82717| 82716| 0.001 | 0.002 | -0.01 |
| 3       | 9.89| 9.67| 99196| 99195| 48.93| 46.75| 82712| 82709| 0.006 | 0.008 | 0.01 |
| 4       | 9.89| 9.54| 99194| 99193| 48.92| 45.48| 82711| 82706| 0.002 | 0.004 | 0.894 |
| 5       | 9.90| 9.50| 99193| 99191| 49.02| 45.12| 82710| 82704| 0.001 | 0.002 | 2.668 |
| 6       | 9.90| 9.47| 99189| 99185| 49.00| 44.89| 82707| 82699| 0.003 | 0.006 | 2.7 |
| 7       | 9.90| 9.45| 99188| 99184| 49.02| 44.62| 82705| 82698| 0.002 | 0.002 | 3.576 |
| 8       | 9.90| 9.47| 99188| 99186| 49.04| 44.80| 82706| 82699| 0.000 | -0.002 | 5.364 |

*AD, Actuator Disk, **OG, Overset Grids

Figure 10. Velocity contours on the 7th and 8th cut planes for TSR=4.75 (top: AD bottom: OG).

The thrust and power coefficients of the downstream turbine are calculated by both methods for different tip speed ratios of the downstream turbine with the tip speed ratio of 6 for the upstream turbine. The thrust and power coefficients of downstream turbine as a function of the tip speed ratios are given in Figures 11 and 12. In Figure 11, it can be observed that the overset grid methodology captures the thrust coefficient in good agreement compared to the experimental data [16], regardless of
tip speed ratio. The actuator disk model, on the other hand, under-predicts the thrust coefficient by a fair margin at low speed ratios. Comparing the power coefficients in Figure 12, the overset grid methodology shows good agreement with the experimental results, whereas the actuator disk model results deviates from the experimental data by a large margin at high tip speed ratios.

Figure 11. Thrust coefficients of downstream turbine for different tip speed ratios.

Figure 12. Power coefficients of downstream turbine for different tip speed ratios.

A detailed wake analysis study is also performed. The non-dimensional streamwise velocity \( (U/U_{\text{ref}}) \), where \( U_{\text{ref}} \) is free stream velocity of the tunnel which is equal to 10 m/s) along the horizontal diagonal through of the rotor axis at position \( x/D = 1 \) and 3 from the downstream turbine rotor is carried out for actuator disk model in Figures 13-15.

At TSR 3.50, there is not much to distinguish between the results of the actuator disk model and overset grid methodology as shown in Figure 13. Actually, the actuator disk model results are closer to experimental data in the core region of the tunnel. From Figure 12, it can be observed the power coefficient calculated from the two methods is almost the same. Taking in the account the high
computational cost involved in performing overset grid calculations, the actuator disk model seems preferable.

At TSR 4.75, the overset grid methodology seems to better capture the wake behaviour when compared to actuator disk model as shown in Figure 14. The wake as calculated by actuator disk model is not far from the experimental data. However, looking at the thrust and power coefficients from Figure 11 and 12, the overset grid methodology is in good agreement with the experimental data unlike the actuator disk model.

At the highest TSR considered, the advantage of using overset grids becomes evident as shown in Figure 15. Using overset grids it is possible to capture both the wake behaviour and the velocity values better, while at the same time calculating the power and thrust coefficients more accurately. The actuator disk model shows shortcomings at this TSR by over-predicting power coefficient and failing to capture the wake behaviour adequately.

Figure 13. Non-dimensional velocity profile along the horizontal diagonal at x/D=1 (left) and x/D=3 (right) for TSR=3.5.

Figure 14. Non-dimensional velocity profile along the horizontal diagonal at x/D=1 (left) and x/D=3 (right) for TSR=4.75.
4. Conclusion

The flow over the two axially non-aligned wind turbines is investigated by performing 3-D CFD simulations with two different numerical approaches. The thrust and power coefficients of the downstream turbine for different tip speed ratios are calculated and compared with experimental results of NTNU BT3. It is observed that there are differences in the results according to the method used. While the actuator disk model tends to under-predict the thrust coefficient until the tip speed ratio of 8, the overset grid methodology predicts the thrust coefficient in good agreement with the experimental results at all tip speed ratios taken into consideration. The actuator disk model is able to predict the power coefficient until the tip speed ratio of 4, and beyond this tip speed ratio, it over-predicts the power coefficient. On the other hand, the overset grid method shows good agreement with the experiments for the power coefficient regardless of the tip speed ratio.

The horizontal velocity profiles after the downstream turbine is compared with the experimental data for different axial locations and tip speed ratios. It is observed the actuator disk model obtains acceptable wake profiles at lower tip speed ratios with less computational expense, therefore it might be preferable employ the actuator disk model at lower tip speed ratios. However at high tip speed ratios, the calculated wake profile deviates further from the experimental data. At low tip speed ratios, the wake profiles calculated by using overset grids are not much better that those calculated by the actuator disk model. Nevertheless, at higher tip speed ratios, the advantages of using the overset grid method become evident. In conclusion, it can be stated that the actuator disk model can be relied upon at low TSR to simulate the case considered. At high TSR however, even though being computationally more expensive, the overset grid methodology gives better results than the actuator disk model.

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