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Actuator Line/Navier Stokes Computations for Flows past the Yawed MEXICO Rotor

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ABSTRACT

In the paper the Actuator Line/Navier-Stokes model has been used to simulate flows past the yawed MEXICO rotor. The computed loads as well as the velocity field behind the yawed rotor are compared to detailed pressure and PIV measurements which were carried out in the EU funded MEXICO project. The computed loading follows in general the experimental counterpart in a period of rotation with a slight overprediction on the mean loading which probably is caused by the inaccuracy of the airfoil data. The predicted wake velocity agrees well with the experiments in the near wake region. Computations with the DNW wind tunnel for the yawed rotor are also performed and show that the tunnel effects are very small in the loading and in the near wake field behind the rotor whereas in the far wake region (>1D) the influence becomes important.

1. INTRODUCTION

In order to precisely predict the performance of wind turbines in wind farms, it is required to have a detailed knowledge on the inflow conditions in front of the turbines which are usually created by the atmospheric turbulence, the ground and the upstream turbines. To compute such complex flows, using a standard CFD code, which solves both the boundary layer on the blades and the wake, is too expensive. In order to reduce computing costs, the Actuator Line/Navier-Stokes technique [1] was developed at Technical University of Denmark (DTU) such that the procedure of solving the boundary layer is skipped and the loading on the rotor blades is represented by using body forces. This enables more mesh points to be used in the wake region or in the flow regions between the turbines. The Actuator line model has been further developed by including the atmospheric turbulence and the wind shear by using the immersed boundary technique for flows past two wind turbines [2, 3]. In order to include the influence of landscape, a hybrid Actuator Line/Navier-Stokes model has been developed where the rotor is solved with the Actuator Line model and the ground is solved with a standard Navier-Stokes solver for Very Large Eddy Simulation (VLES). The flow past a wind turbine on a hill was recently simulated in [4].

To validate computational models in the case of a real wind turbine, NREL [5] made its two-bladed Phase VI turbine with a diameter of 10 m and tested it in the NASA/Ames 80ftx120ft wind tunnel. The obtained results were used by the wind turbine research community to validate computational codes. As in wind farms wind turbines are clustered in array, one wind turbine may be located in the wake of another wind turbine. This means that the wake created from the front turbine has big influences on the performance of the wind turbine in wake. Therefore the ability of predicting a correct wake structure is very important for an aerodynamic model. In the NREL experiments, detailed flow measurements using techniques such as hotwires, Laser Doppler Anemometry (LDA) or Particle Image Velocimetry (PIV) were not present and the predicted wake structure behind the wind turbine could not be validated. Under this circumstance, the MEXICO (Model Experiments in Controlled Conditions) project [6, 7] funded by the European Commission was created. The MEXICO rotor with a diameter of 4.5 m was constructed during the project. It has three blades composed of a cylinder from 0% to 4.4%, the DU91-W2-250 airfoil from 11.8% to 40% span, the RISOE-A1-21 airfoil from 50% to 62% span and the NACA 64-418 airfoil from 72% to 100% span, and three transitional zones between the airfoils. The rotor has a diameter of 4.5 m and was tested in the DNW German-Dutch wind tunnel with an open cross-section of 9.5x9.5 m^2 where both measurements using pressure taps and PIV were carried out.

An important check is whether the AL/NS technique can predict correctly the loads on the blades and the wake behind the turbines. In the first part of the MexNext project [8], the AL/NS technique has been validated against detailed measurements for the MEXICO rotor in standard conditions [9, 10]. Results showed that the model can predict the loading and the wake with good accuracy.

For a wind turbine, the wind direction is not perpendicular to its rotor plane in most of its operations even a yaw control is active. Therefore the prediction of a yawed wind turbine is rather important for studying wind turbine aerodynamics in wind farms. In this paper, the validation of the AL/NS technique for flows past the yawed MEXICO rotor is carried out.

2. NUMERICAL METHODS

The numerical method used in the paper is the actuator line/Navier-Stokes model which has been developed in [1-4, 9-10]. For more details about the methodology, the reader is referred to these papers.

3. RESULTS

3.1 Computations without tunnel

Computations for flows past the MEXICO rotor at a rotational speed of 424 rpm, a pitch angle of -2.3 deg, wind speeds of 10, 15, 24 m/s and yaw angle of 15^o, 30^o and 45^o were carried out by employing the AL/NS model on a Cartesian mesh consisting of 11.8 M mesh points in a domain of [-16R, 16R]×[-16R, 16R]×[-16R, 16R], with the finest mesh size of R/30 where R is the rotor radius. Two sets of airfoil data: original airfoil data (OAD) and modified airfoil data (MAD) are used for flows past the yawed MEXICO rotor. For more information about the airfoil data, the reader is referred to [10]. To validate the computations (with MAD), the force distributions during one revolution are compared to the DNW measurements in Figs. 1 and 2. Fig. 1 shows the loading at a wind speed of 10 m/s and a yaw angle of 30^o. The normal force at radial positions of 35%, 60%, 82% r/R follows quite well the experiments while at 92% r/R a phase shift occurs between the computations and the experiments. The variation of the computed tangential force agrees in general with the measurements with slight over-predictions of the mean tangential force. In Fig. 2, the force distribution at a wind speed of 15 m/s and a yaw angle of 45^o is plotted. From the figure, good agreements for both normal and tangential force are seen between the computations and the measurements.

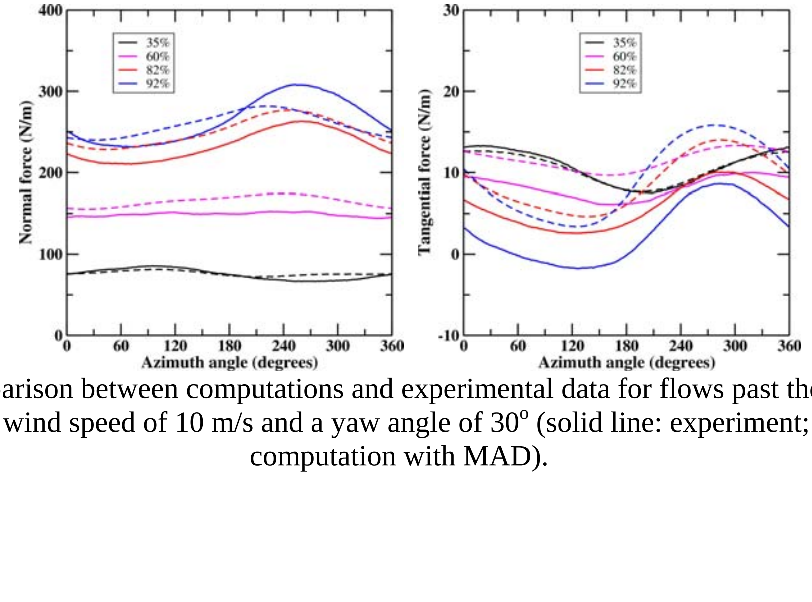

Figure 1: Comparison between computations and experimental data for flows past the MEXICO 25 kW rotor at a wind speed of 10 m/s and a yaw angle of 30^o (solid line: experiment; dashed line: computation with MAD).

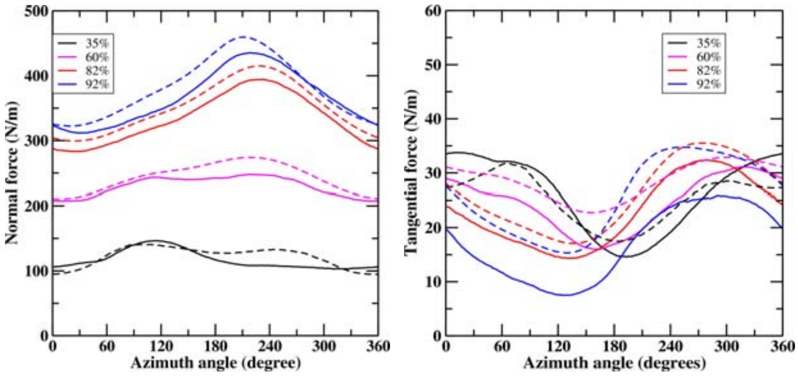

Figure 2: Comparison between computations and experimental data for flows past the MEXICO 25 kW rotor at a wind speed of 15 m/s and a yaw angle of 45^o (solid line: experiment; dashed line: computation with MAD).

In order to validate the flow field behind the yawed rotor, the velocity field along two lines in the flow direction at 9 o'clock and two positions of x=1.377 m and x=1.848 m in the tunnel coordinates is extracted. In Fig. 3, the velocity components at x=1.377 m in the tunnel coordinates are compared to the experiments for flows past the Mexico rotor at -30 deg yaw and a wind speed of 15 m/s. From the figure, computations with both sets of airfoil data agree well with experiments. The most remarkable difference is seen for the horizontal velocity in which the MAD computations over-predict slightly the values. It is worthwhile notating that the velocity in computation has smaller fluctuations than in experiment. This is caused by the too coarse mesh used in the computations at 15 m/s. The situation becomes much better for a wind speed of 24 m/s [10]. The velocity components at x=1.848 m for flows past the yawed rotor at 30 deg yaw and a wind speed of 15 m/s are shown in Fig. 4. Qualitatively good agreements are seen for computations with both airfoil data.

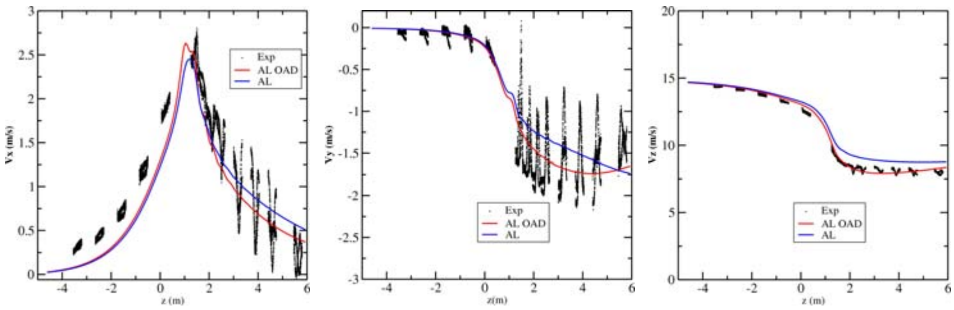

Figure 3: Spanwise, vertical and horizontal velocity in tunnel coordinates at r=1.377 m for flows past the MEXICO rotor at a wind speed of 15 m/s and a yaw angle of -30^o.

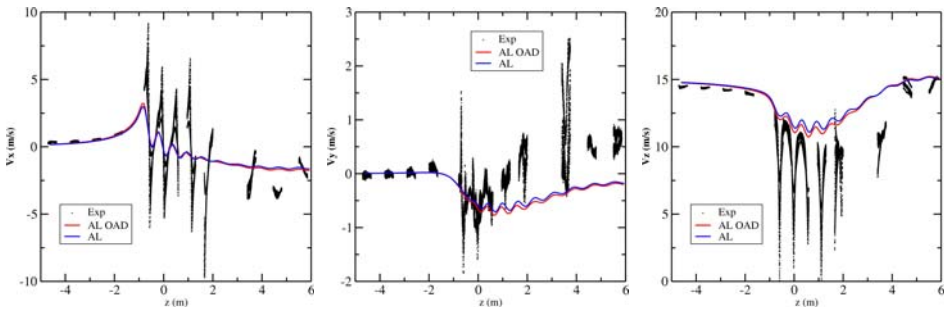

Figure 4: Spanwise, vertical and horizontal velocity in tunnel coordinates at r=1.848 m for flows past the MEXICO rotor at a wind speed of 15 m/s and a yaw angle of 30^o.

The radial, tangential and axial velocity components in the rotor coordinates are also plotted. In Fig. 5, the velocity at 0.15 m before the rotor is compared to measurement. From the figure, good agreements are seen. The velocity at 0.15 m after the rotor is also plotted and compared to experiment in Fig. 6. Excellent agreements are seen. It is worth noting that in the tip region big velocity changes are seen in the experiments where a smooth transition occurs in the computations. This is probably caused by the too coarse mesh used in the computations.

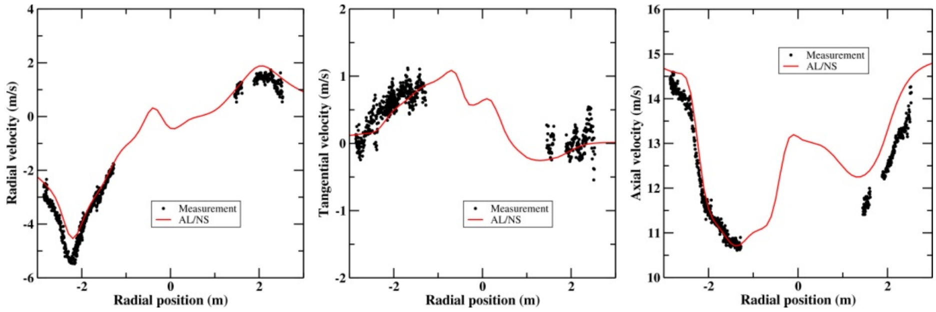

Figure 5: Radial, tangential and axial velocity at 0.15 m before the rotor for flows past the MEXICO rotor at a wind speed of 15 m/s and a yaw angle of 30°.

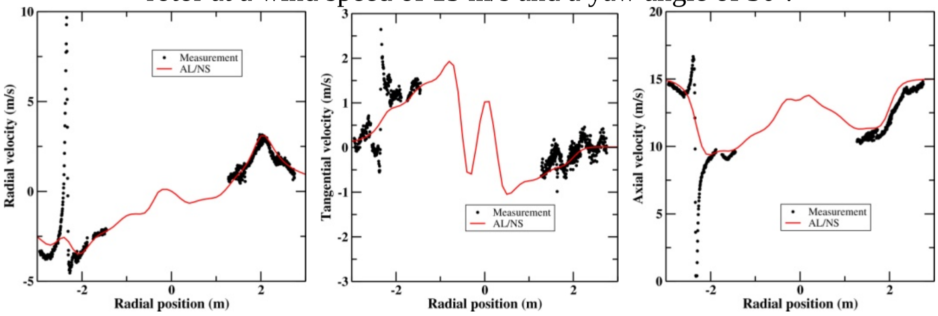

Figure 6: Radial, tangential and axial velocity at 0.15 m after the rotor for flows past the MEXICO rotor at a wind speed of 15 m/s and a yaw angle of 30°.

In order to show the structure behind a yawed rotor, iso-vorticity is plotted in Fig. 7. The structure shows that the wake develops first in the axial direction, and then bends to a direction with an angle which is slightly negative (below the wind direction).

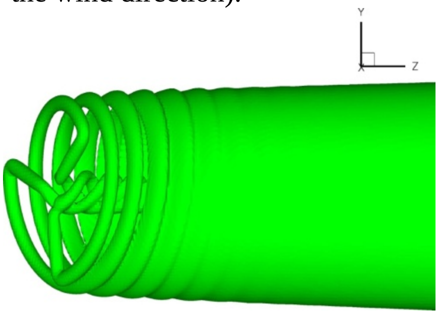

Figure 7: Iso-vorticity surface plot for flows past the MEXICO rotor at a wind speed of 15 m/s and a yaw angle of 30°.

3.2 Computations with the DNW tunnel

In order to check the influence of the DNW tunnel on the performance of the MEXICO rotor in yaw, computations with the DNW tunnel are also performed. The detailed dimensions of the DNW tunnel can be found in [6]. To make the computations, a nearly Cartesian mesh of 100 blocks with 26.2 M mesh points is used. 36 blocks are used in the open tunnel with a cross-section of 9.5x9.5 m^2 and 64 blocks are used in the room outside of the open tunnel. The finest mesh is located near the rotor plane with a cell size of *R*/30. In Fig. 8, the normal and tangential forces for flows past the MEXICO rotor at a wind speed of 15 m/s and a yaw angle of 30° are plotted against the measurements. From the figure, it is seen that the force computed with the tunnel (dotted lines) is only slightly bigger than that in free air but the differences are quite small. The spanwise, vertical and horizontal velocity components in the tunnel coordinates are also compared to the measurements and the computations in free air in Fig.

9. For the spanwise velocity, the computation with tunnel agrees better with measurements especially in the wake region. The same tendency is also seen for the vertical velocity. Concerning the horizontal velocity, the changes are not significant. Remark that the experimental horizontal velocity drops quite a lot at a distance of about one diameter after the rotor. This drop cannot be predicted from our computations.

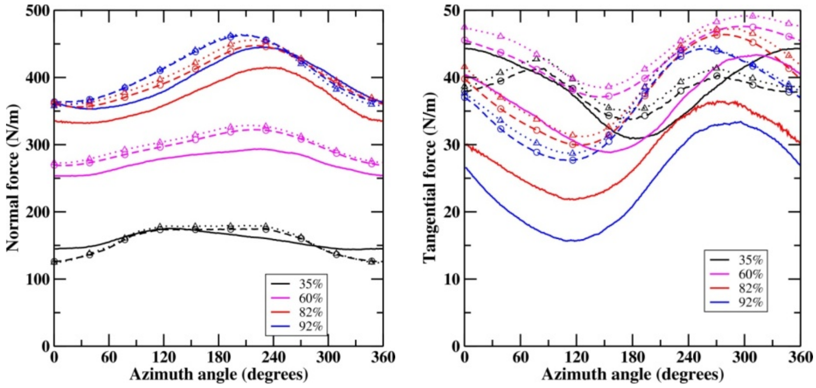

Figure 8: Comparison between computations and experimental data for flows past the MEXICO rotor at a wind speed of 15 m/s and a yaw angle of 30^{o}(solid line: experiment; dashed line: computation with MAD in free air; dotted line: computation with MAD with tunnel).

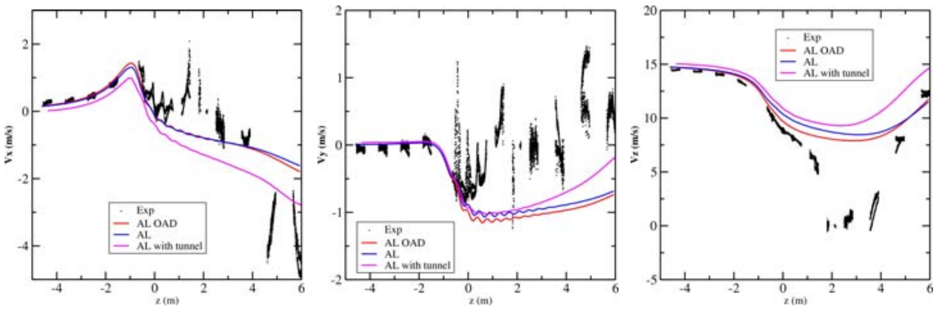

Figure 9: Spanwise, vertical and horizontal velocity in tunnel coordinates at r=1.377 m for flows past the MEXICO rotor at a wind speed of 15 m/s and a yaw angle of 30^{o}.

3. CONCLUSION

The Actuator Line / Navier-Stokes model has been validated for both loading and velocity field against the MEXICO measurements for flows past the yawed MEXICO rotor. In general, the model can predict correctly the force changes during a revolution. The velocity behind the rotor can also be predicted correctly in the near field. Computations with the DNW tunnel can improve the velocity prediction in the far wake. From the study we can conclude that the AL/NS model is ready to simulate flows past a wind turbine in yaw and to simulate complex flows in wind farms.

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