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Study on Wind Turbine Arrangement for Offshore Wind Farms

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Abstract

In this paper, the separation distance between two neighboring offshore wind turbines has been carried out by using the Actuator Line/Navier-Stokes technique developed at the Technical University of Denmark (DTU). Under offshore atmospheric conditions, Large Eddy Simulation has been performed for two Tjæreborg 2 MW wind turbines in tandem with separation distances of 4D, 5D, 6D, 7D, 8D and 10D at the design wind speed of 10 m/s. The power performance of the wake turbine showed to be about 23% of the first turbine at a separation distance of 4D while its performance reached about 50% at 7D due to the turbulence mixing. This study hints that the optimal separation distance between neighboring turbines for offshore wind farms should be 7 rotor diameters.

Nomenclature

D   diameter of a wind turbine
H   hub height
V   wind shear velocity
V_H velocity at hub height
y   vertical coordinate
α   wind shear exponent

Introduction

The arrangement of wind turbines in wind farms plays an important role for wind turbines to extract wind energy efficiently from the wind. Due to the wakes created by the front turbines, the energy extracted by a downwind wind turbine is often influenced very much by the separation distance between two neighboring turbines. The energy/wind speed in the wake of a turbine recovers gradually due to the effect of turbulence mixing. Depending on the local turbulence characteristics in atmospherics, the speed of the recovery is very different at onshore and offshore sites.

Simple models of studying the wind turbine wake effects were developed in [1] [2] [3] which are based on simple wake calculations. As these models cannot predict correctly the turbulence characteristics in the wake, the performance of the downstream turbines cannot be predicted accurately. To improve the wake resolution, the Actuator Line / Navier-Stokes technique were developed at the Technical University of Denmark (DTU) [4] in which the procedure of solving the boundary layer of the rotating blades is skipped and instead the loading on the rotor blades is represented by using body forces. This enables more mesh points to be used in the wake region and in the flow regions between the turbines. The model has been applied and validated for studying the wake interaction between two 2MW NM80 wind turbines [5] for a separation distance of 6.6D under inflow conditions on a flat terrain at the Tjæreborg Enge site.

In the present paper, we study on the power performance of the downstream turbine in function of the separation distance under the offshore atmospheric turbulence.

Numerical method

In this section, the numerical model for simulating wind turbine flows under offshore atmospheric conditions is presented.

Under stable conditions, the flow is governed by the incompressible Navier-Stokes equations. The finite volume code EllipSys3D developed at DTU and RISØ [6] [7] is used. The wind turbines are modeled by using the Actuator Line/Navier-Stokes model developed at DTU [4] where the procedure of solving the boundary layer is skipped and instead the loading on the rotor blades is represented by using body forces. This enables more mesh points to be used in the wake region and in the flow regions between the turbines. For more details about the Actuator Line technique, the reader is referred to [4] [5] [8].

The wind shear profile is the power law as

$$V = V_H \left(\frac{y}{H} \right)^\alpha \qquad (1)$$

where H is the height of the turbine hub, V_H is the wind speed at the hub height and α is the exponent of the wind shear profile. For offshore application, an exponent of 0.1 is used.

The atmospheric turbulence is introduced in a box in front of the first turbine by using the Mann algorithm [9] which is based on spectral tensor modeled using the rapid distortion theory combined with a model for eddy lifetime. At a standard offshore site, the turbulence box creates a turbulence field with a turbulence level of 5.5% at a hub wind speed of 10 m/s.

The wind shear and the atmospheric turbulence are introduced in the EllipSys3D code by using body forces. For more details, the reader is referred to [5] [10].

<div align="center">

Results

</div>

Computations for flows past two pitch regulated Tjæreborg 2MW wind turbines in tandem on an offshore site are carried out. The turbine has a diameter of 61.2 m and runs at 22.1 rpm. It reaches its rated power of 2 MW at a wind speed of 15 m/s. The tower height of the two turbines is 1 rotor diameter (D) above the sea level. A Cartesian mesh consisting of 18.9 M mesh points is used in a domain of [-8D, 8D]×[-1D, 9D]×[-8D, 17D] where the origin is chosen to be the rotor centre of the first turbine. A uniform mesh with a size of R/30 where R is the rotor radius is used in the central part near the rotor in both transversal and vertical directions while a uniform mesh with a size of R/18 is used in the wind direction from [-0.5D, 11.5D]. Six separation distances of 4D, 5D, 6D, 7D, 8D and 10D between the two turbines are considered.
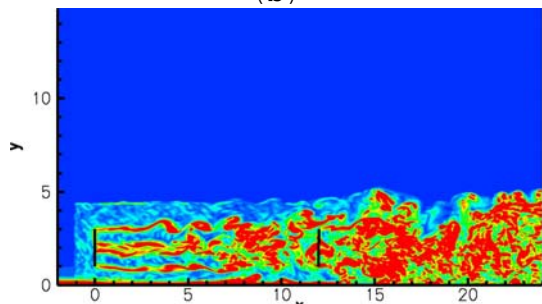
Wind speed of 10 m/s

In Figure 1, iso-vorticity plot is shown for flows past the two turbines at a hub-height wind speed of 10 m/s and separation distances of 4D, 6D, 8D and 10D. From the figure, it is seen that turbulence eddies are created from the turbulence box located at 0.5D in front of the upstream turbine. When it reaches to the first turbine, it interacts with the tip and root vortices which can be seen clearly from the plots. The tip vortices are merged with the turbulence eddies at about 4D and after that a meandering structure is developed at about 7D. This phenomenon can also be seen in the time-averaged axial velocity plots in Figure 2. From Figure 2(a), the downstream turbine located at 4D behind the upstream turbine is completely in the wake. When the separation distance is 6D, it is seen in Figure 2(b) that the downstream turbine is only partly influenced by the wake of the first turbine while the turbine is almost out of the wake influence for a separation distance of 8D. The standard deviation of the velocity in the wind direction is plotted in Figure 3. From the figure, it is seen that the downstream turbine is located in the region of the highest turbulence level, Figure 3(a). At a distance of 6D (Figure 3(b)), the turbine is at the edge of the region of the highest turbulence level. The
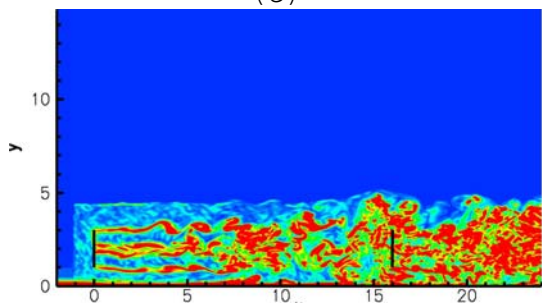
downstream turbine at 8D is seen to be far from this region.
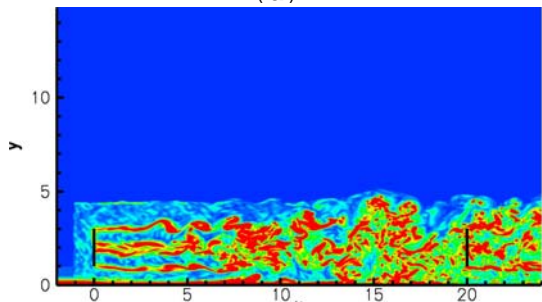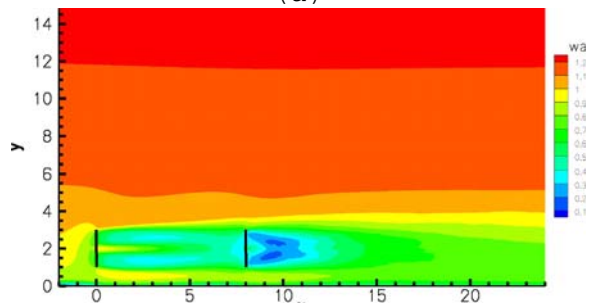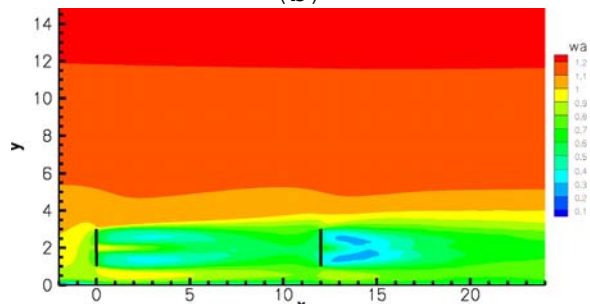
(a)
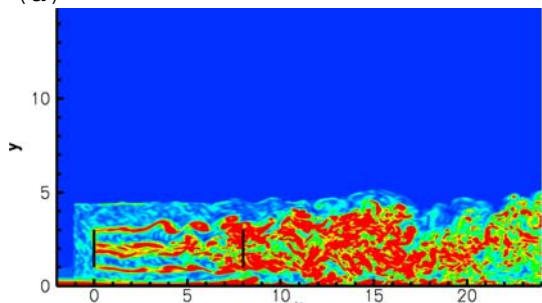
(b)

(c)

(d)

Figure 1: Iso vorticity plot of flows past two 2MW Tjæreborg turbines in tandem at a hub wind speed of 10 m/s with separation distances of (a) 4D; (b) 6D; (c) 8D; (d) 10D.
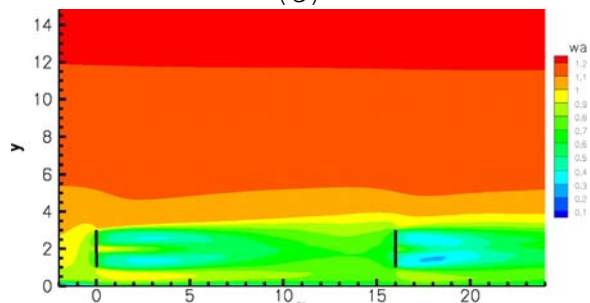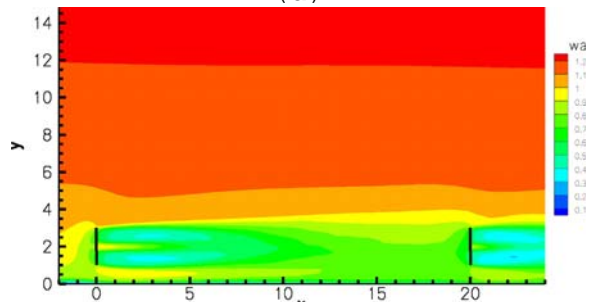
(a)

(b)

(c)

(d)

Figure 2: Iso-axial velocity plot of flows past two 2MW Tjæreborg turbines at a hub wind speed of 10 m/s with separation distances of (a) 4D; (b) 6D; (c) 8D; (d) 10D.
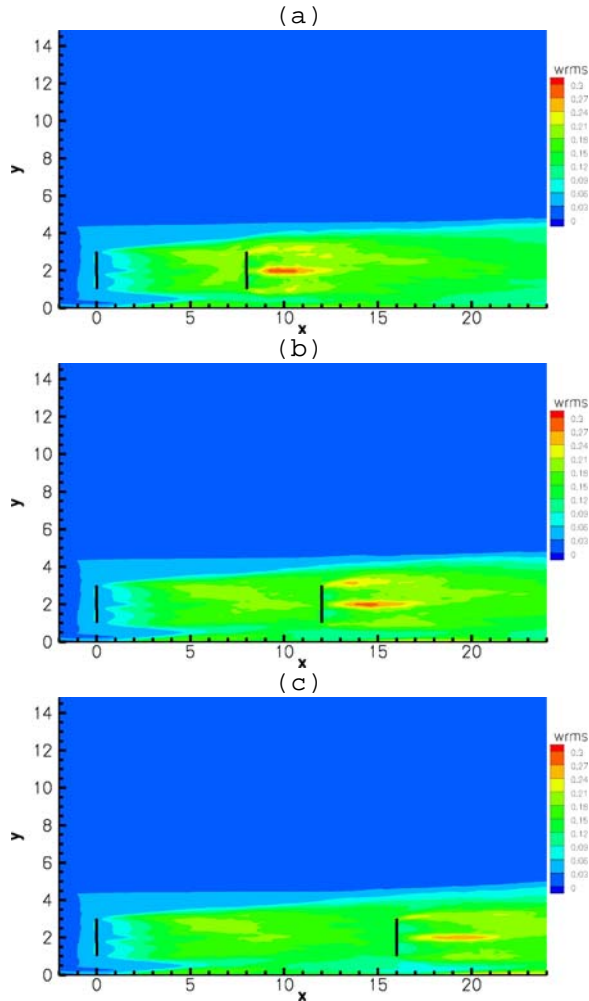
(a)

(b)

(c)

Figure 3: Axial standard deviation plot for flows past two 2MW Tjæreborg turbines at a hub wind speed of 10 m/s with separation distances of (a) 4D; (b) 6D; (c) 8D.
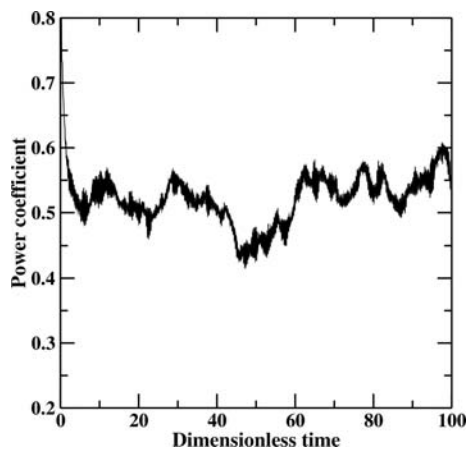

Figure 4: Power coefficient of the upstream turbine at a hub wind speed of 10 m/s.
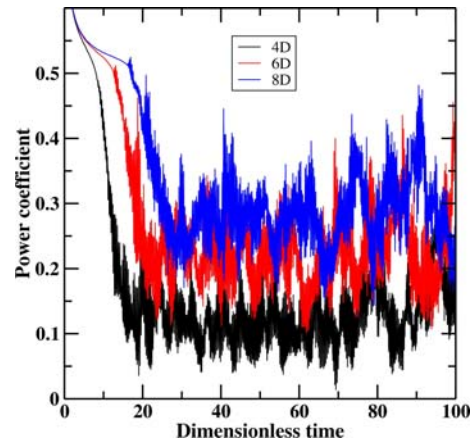

Figure 5: Power coefficient of the wake turbine at a hub wind speed of 10 m/s and different separation distances.
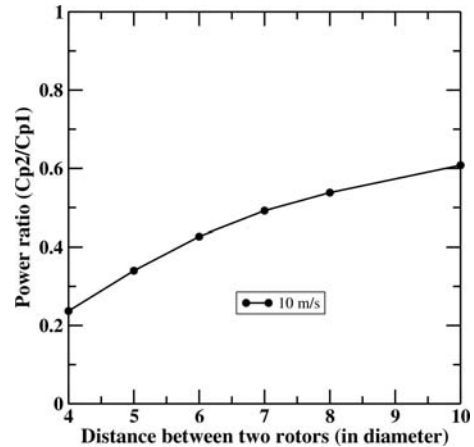

Figure 6: The ratio between the power coefficients of the two turbines at a wind speed of 10 m/s.

The power coefficient is the upstream turbine is plotted in Figure 4. From the figure, it is seen that the curve is fluctuating because of the atmospheric turbulence. The averaged power coefficient is found to be 0.52 which corresponds to the design point. It is worth noting that the power coefficient of the upstream turbine is almost independent of the separation distance with the downstream turbine. The power coefficient of the downstream turbine is plotted in Figure 5 for separation distances of 4D, 6D and 8D. From the figure, the

fluctuations are seen to be much more important than those in the power coefficient of the first turbine. It can also be seen that the power increases when the separation distance increases. The ratio of the power coefficients from the second and first turbines is plotted in Figure 6. From the figure, it is seen that the power coefficient ratio is only about 23% at 4D, and increases to about 50% at 7D and 60% at 10D.

From the above study, it can be concluded that the separation distance between two neighboring turbines in offshore wind farms should be at least 7D.

Wind speed of 12 m/s

In order to see the picture at another wind speed, computations are carried out for the two turbines at a separation distance of 7D and a wind speed of 12 m/s. Iso-vorticity plot is shown in Figure 7. The eddy intensity is seen to be smaller in the case of 12 m/s while the wake structure is quite similar to that at 10 m/s. The time-averaged standard deviation of the axial velocity is plotted in Figure 8. From the figure, it is seen that the wrms is smaller in the case of 12 m/s because there are wake revolutions in the same distance between two turbines. The power coefficient of the upstream turbine is similar to that plotted in Figure 4 with an averaged power coefficient of 0.48. The power performance of the downstream turbine is also similar to that at a hub wind speed of 10 m/s.

From the above study, it can be concluded that the wake blockage is not sensitive to wind speed.
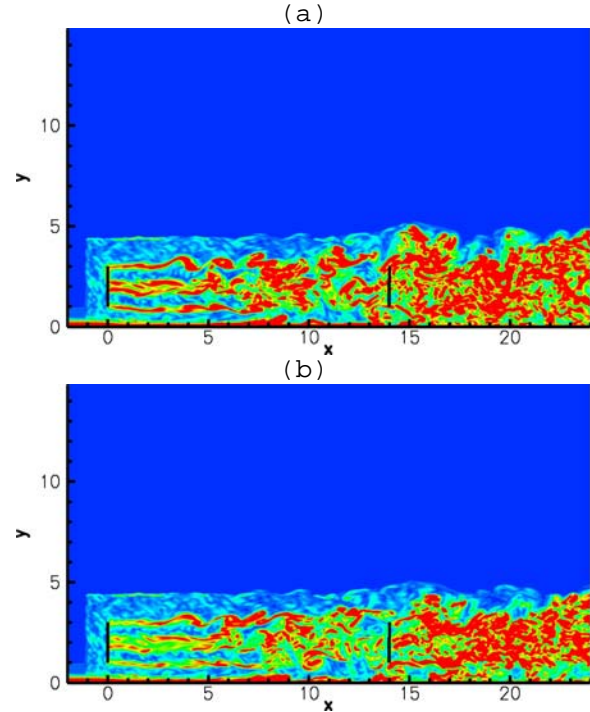

Figure 7: Iso-vorticity plot of flows past two 2MW tjæreborg wind turbines at a separation distance of 7D and hub wind speeds of (a) 10 m/s; (b) 12 m/s.
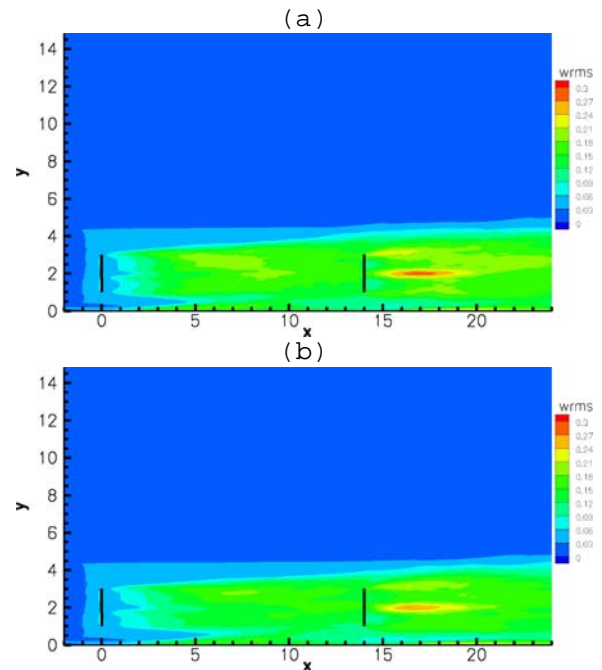

Figure 8: Axial standard deviation of flows past two 2MW tjæreborg wind turbines at a separation distance of 7D and hub wind speeds of (a) 10 m/s; (b) 12 m/s.

Conclusions

The separation distance between two neighboring turbines has been studied by using the Actuator Line/Navier-Stokes model under an offshore atmospheric turbulence and wind shear. The outcome showed that the power coefficient of the downstream turbine can reach about 50% at a separation distance of 7D. This distance is therefore suggested to be used for planning offshore wind farms.

Acknowledgement

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