

Tilted wind turbines in farm configuration for improved global efficiency

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Abstract. The advance in wind turbine technology has led to a tendency to gather the turbines into wind farms to benefit from economies of scale. However, the farm configuration often leads to a drastic power loss due to the interactions between the turbines. To mitigate this issue, the turbines are typically misaligned with the dominant wind direction to deviate their wake. In this paper, a tilt-induced wake deviation strategy is studied in a farm configuration using large eddy simulation of an atmospheric boundary layer and an actuator line model for the blade. The results show an effective wake deviation and a significant increase of the total power production of the farm. The evolution of the time-averaged and unsteady loads is also assessed in the wind farm, and the resulting damage equivalent load is shown to be reasonably modified when the turbines are tilted. The tilted configuration is also compared with a wind farm with yawed turbines and is found to lead to a larger power output for a reduced damage equivalent load.

1. Introduction

Nowadays, offshore wind turbines are generally gathered into wind farms to reduce the cost of the installation work and of the transportation capacity extension. However, this clustering increases the interactions between the turbines and can therefore drastically hinder the power extraction. For example, power losses up to 40% were observed when the turbines are aligned with the wind direction [1].

A possible strategy to mitigate this problem consists in misaligning the rotor relatively to the wind direction by applying a yaw angle, as illustrated in Fig. 1. As a result, the turbine thrust has a lateral component that deflects the wake away from the downstream turbine, resulting in an increased power production [2, 3, 4]. Another possible approach consists in tilting the turbines instead of yawing them. This is possible by placing the rotor in a downwind configuration. The three major potential advantages of tilting over yawing are the increased wake recovery rate due to the ground interaction, the limitation of the interactions between the lines and the improvement of the power production by entraining higher velocities from the upper part of the atmospheric boundary layer (ABL).

To date, only few studies have been performed on the effects of the tilt angle in wind farms. Abdelsalam & Ramalingam [5] used the Reynolds averaged Navier-Stokes equations to show that tilting effectively increases the wake recovery and obtained a considerable gain of available power downstream. Fleming *et al.* [6] used large eddy simulation (LES) to observe the wake

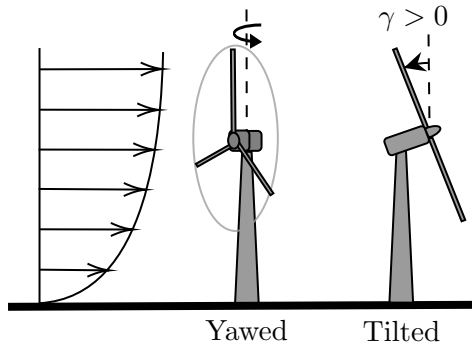


Figure 1: Yawed (rotation around the vertical axis) or tilted (rotation around the spanwise axis) configurations. The angle γ is defined positive when the turbine is tilted upwards.

deviation behind a tilted rotor and the increase of the bending moment on the blades. Annoni *et al.* [7] studied the interaction of two or three wind turbines using LES and obtained a significant total power gain by using an important tilt angle. However, none of those studies investigated a sufficiently large number of wind turbines in a farm configuration, nor assessed the interactions between multiple turbines lines. Moreover, the unsteady loads acting on the blades were not quantified in tilted cases. The objectives of this paper are to perform high fidelity LES of a wind farm in a realistic ABL and using an actuator line model (ALM) to investigate the effect of the tilt angle on the power, loads and turbine wakes. To evaluate the improvements obtained by tilting, the aforementioned characteristics are also compared to a farm containing yawed turbines.

This paper is as follows: section 2 introduces the methodology used to perform a realistic LES of a wind farm. The different studied cases, as well as the numerical parameters, are also defined. Section 3 presents and discusses the characteristics of a wind farm containing turbines aligned with the wind direction. Three major aspects are discussed: the farm flow topology, the steady and unsteady loads acting on the blades and the power output of the global system. The last section concludes the discussion and offers new perspectives.

2. Methodology

2.1. Flow solver

We consider the LES of turbulent flows, performed using a in-house fourth-order finite differences code [8, 9]. The code solves the incompressible Navier-Stokes equations supplemented by a subgrid scale model (here, a classical Smagorinsky approach [10] further supplemented with a near-wall closure model). To simulate a realistic ABL, one wind farm simulation implies two concurrent simulations. The main one actually involves the wind turbines, while the auxiliary one is used for generating the inflow conditions. For the auxiliary simulation, periodic conditions are used in the horizontal directions, while a no-slip wall is used at the top. At the bottom, a wall stress model [11] for a rough surface is applied. The flow is driven by an imposed pressure gradient, here chosen to obtain the desired hub velocity and turbulence intensity (TI). This auxiliary simulation runs concurrently with the main simulation, which allows inflow conditions to be directly transferred to the inlet of the main domain. For the main simulation, outflow conditions are imposed at the outlet boundary and periodic conditions are kept in the spanwise direction. Again a wall model and a no-through flow condition are imposed at the bottom and top, respectively. In the present work, thermal and stratification effects are not included, and the resulting simulations are thus equivalent to neutral conditions. The hub velocity of this ABL is 9m/s and the TI is 6%.

The wind turbine blades are modeled using a state-of-the-art actuator line model (ALM) [12]. This model interpolates the flow velocity on a line representing the blade and computes the forces at control points with the blade element theory that uses the experimental lift and

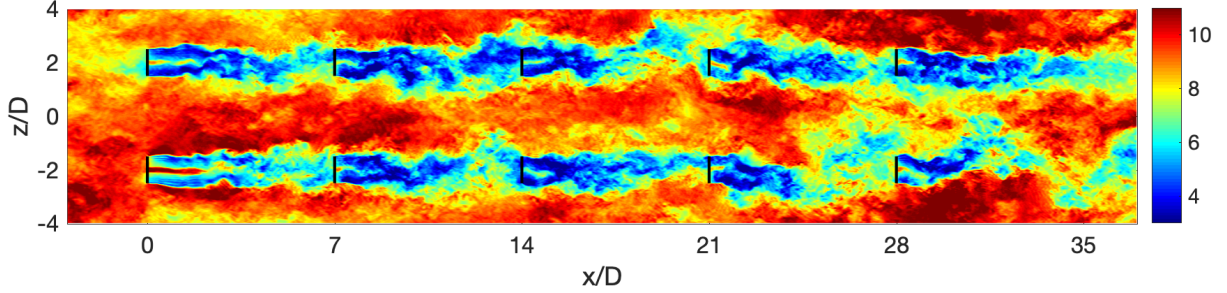


Figure 2: Instantaneous streamwise velocity [m/s] in a horizontal plane located at hub height in the baseline case.

drag coefficient for the considered airfoil. The forces are then mollified on the mesh to avoid instabilities due to a singular forcing term. This step is performed using a 2D non-uniform Gaussian kernel,

$$\eta = \frac{1}{\pi\sigma_c\sigma_t} \exp\left(-\left(\frac{d_c}{\sigma_c}\right)^2\right) \exp\left(-\left(\frac{d_t}{\sigma_t}\right)^2\right)$$

where σ_c and σ_t are the mollification parameters, and d_c and d_t are the distance from the grid point to the blade element in the profile chord and thickness directions respectively. This distribution kernel avoids spanwise mollification and hence produces a consistent tip behaviour without requiring any additional correction [13].

2.2. Numerical setups

The considered wind turbine model is the “NREL offshore 5-MW” baseline wind turbine [14], supplemented by its controller [14]. Ten wind turbines are gathered into two lines of five machines, as depicted on Fig. 2. The streamwise spacing between two turbines is 7D (D being the rotor diameter, defined in [14]), and the spanwise spacing is 4D. The turbines are immersed in a mesh composed of 32 grid points per D in the vertical (y) and transverse (z) directions. The grid is partially stretched in the vertical direction, and starts to increase above the wind turbines to reach $\Delta y_{max}/D = 0.183$ at the top of the domain; this allows to decrease the computational cost. The streamwise (x) spacing is set to $\Delta x = 1.25\Delta y$. The domain size is 40Dx8Dx8D and contains 1024x128x256 grid points.

With an explicit ALM, the blade tip cannot travel more than one mesh cell over a time step. There are thus some limitations on the time step dt , which is here set to 0.04 [s]. This leads to a CFL based on the tip velocity (CFL_{tip}) of about 0.6.

Table 1 contains a summary of the cases investigated in this work. The effects of tilting and yawing are investigated in Section 3 in an aligned arrangement. Two tilt angles are investigated: a realistic 15° case and a more extreme configuration with a tilt of 25° . Those angles would be achieved in practice with a downwind configuration. For the yawed case, only a 25° case is studied to provide a comparison with the strongly tilted case.

3. Results

This section focuses on the effect of tilted wind turbines in an array aligned with the wind direction. This case is the most detrimental as the velocity deficit behind the first turbines directly impacts the downwind ones, and the high turbulence level in the wake increases the unsteady loads. Those matters can be partially reduced using tilting. The wake deviation is

Table 1: Summary of the simulation set ups.

Name	Wind angle	Tilt angle	Yaw angle
Baseline	0°	0°	0°
Moderately tilted	0°	15°	0°
Strongly tilted	0°	25°	0°
Strongly yawed	0°	0°	25°

first investigated by observing the time-averaged velocity and vorticity fields. Then, the mean and unsteady loads are compared to the baseline and yawed cases. Finally, the evolution of the power output is observed for each wind turbine.

3.1. Time-averaged velocity and vorticity

Slices of the time-averaged velocity and vorticity are displayed on Fig. 3. The slices were extracted 3D behind each pair of rotors. For the baseline, the velocity deficit mainly diffuses radially but is not deviated. In the moderately tilted case, the deficit shape is flattened in the vertical direction and spreads horizontally. This behavior is amplified in the strongly tilted case and a lower velocity region appears on the side. In this case, the entrainment of higher velocities in the array is visible past the last turbines. In the yawed case, the deficit is deviated sideways and is deformed into a curled shape (as also observed in [15]). The effect of the deviation is amplified through the farm for the three misaligned cases.

This behaviour is related to the vortex system observable behind the rotor. Whereas the baseline case presents one vortex core corresponding to the turbine rotation, the misaligned cases systematically include an additional pair of contra-rotating vortices. The vortices are aligned horizontally in the tilted case, while they are aligned vertically in the yawed configuration. Those vortex pairs find their origin in the transverse component of the thrust generated by the misaligned rotor. In the case of tilting, they present the disadvantage of pulling up low velocities between the turbines; whether this could be detrimental with turbines not aligned with the wind will be investigated in future work.

3.2. Loads

Tilting a turbine creates an asymmetry between the upwind and the downwind part of the rotor. A higher velocity impacts the upwind part of the rotor as the induced wind speed reduction is lower. The asymmetry is further intensified in the case of tilting as the upper half of the rotor that experiences higher velocities in an ABL is now placed upwind. Moreover, the entrainment of high velocities tends to increase the upper half loads. The blades hence suffer from a larger variation during one rotation, resulting in an increased probability of fatigue failure. This section provides further insights into the evolution of the steady and unsteady loads.

The time-averaged loads over one rotation are first considered. Figure 4 presents the bending moment acting on one blade as a function of its azimuthal position, averaged over the last 150 rotations of the turbine. The flapwise and edgewise moments are presented for the first and the last turbine of the first line. The edgewise moment of the first wind turbine (Fig. 4a) has the highest mean moment in the baseline case due to its alignment with the wind direction. The first yawed rotor undergoes a lower mean value but the amplitude of the variation is similar to the baseline case. On the other hand, the first tilted turbines exhibit a different behaviour. Despite a lower mean edgewise moment, the variation experienced on one rotation is significantly higher. The last turbine of the line (Fig. 4b) is substantially less loaded than the first one in the baseline case and the reduction is essentially uniform over the entire rotor. The yawed turbine

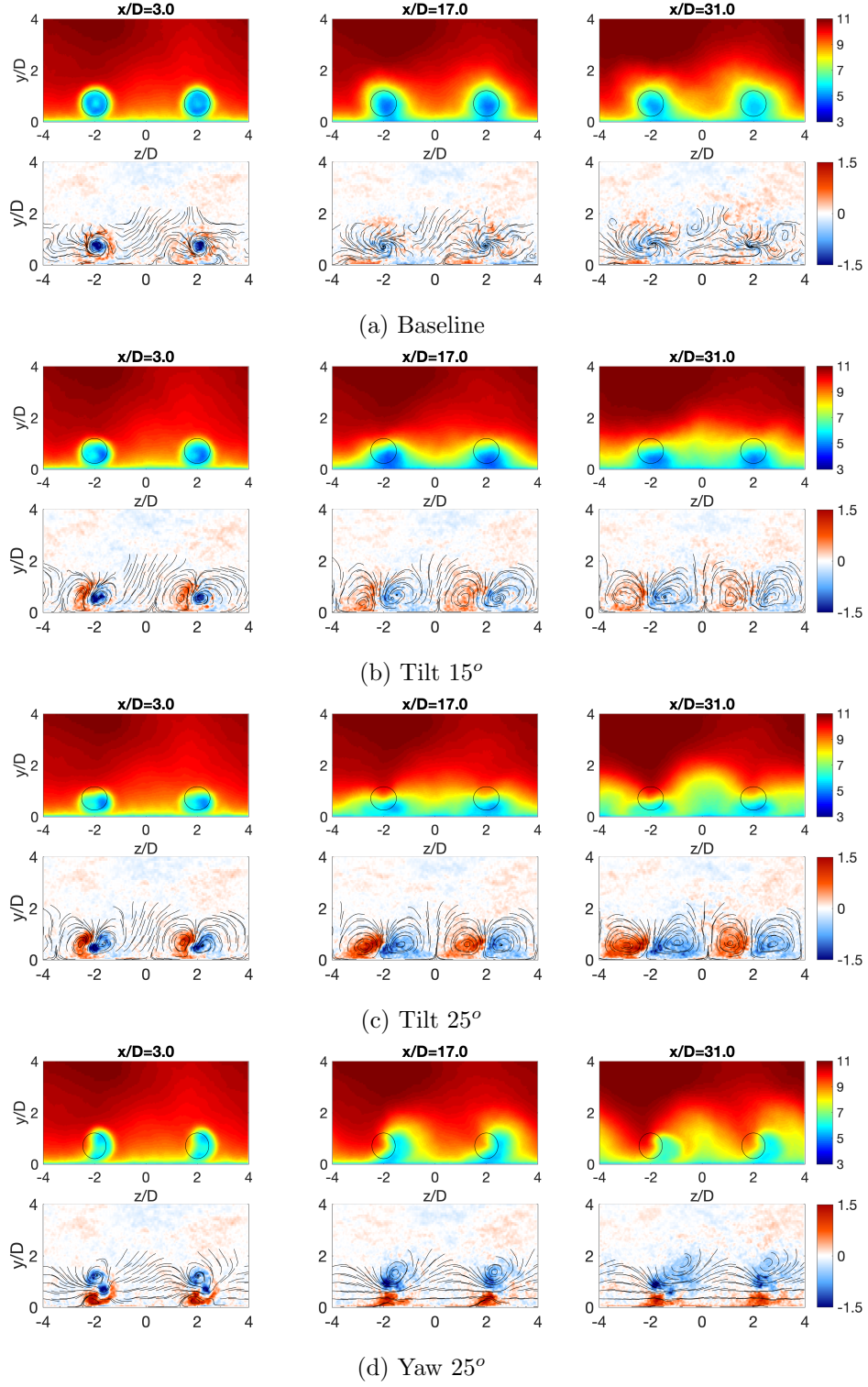
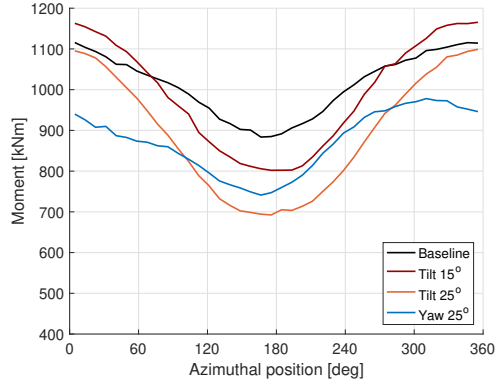
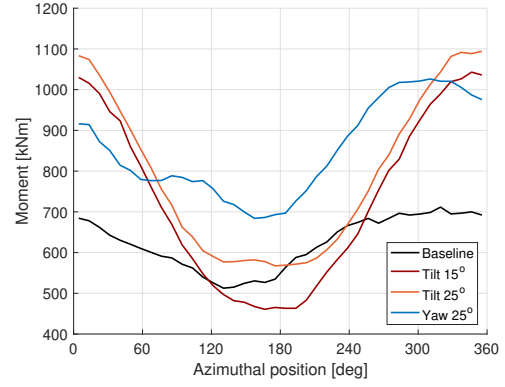


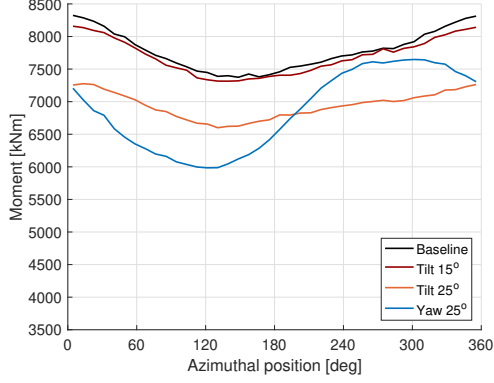
Figure 3: Time-averaged velocity (upper slices, m/s) and vorticity (lower slices, 1/s) fields. The planes are sampled 3D behind the first, third and last rotor pair.



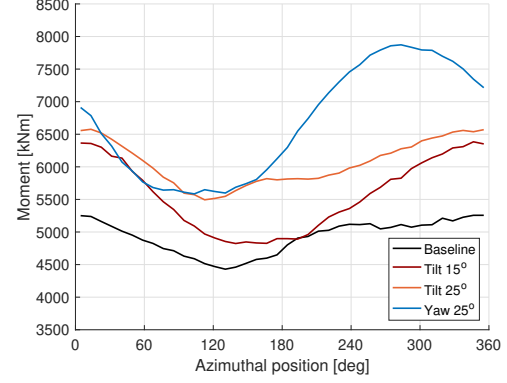
(a) Edgewise bending moment, first wind turbine



(b) Edgewise bending moment, last wind turbine



(c) Flapwise bending moment, first wind turbine



(d) Flapwise bending moment, last wind turbine

Figure 4: Time-averaged bending moment acting on one blade during a rotation (zero corresponds to the vertical upwards position).

experiences a slight increase of the moment in the upwind part of the rotor but the amplitude of the azimuthal variation remains fairly constant. For the last turbine of the tilted cases, the amplitude of the variation has roughly doubled due to the increase of the asymmetry between the upper and lower part of the rotor. Interestingly, the strongly tilted case is more favorable than the moderately tilted one as the lower part of the rotor remains more loaded, reducing the amplitude of the alternation.

The flapwise moment presents a different behaviour. The variation of the moment on the first tilted turbines (Fig. 4c) now has the same amplitude as the baseline, while the variation observed for the yawed case is larger. On the last turbine (Fig. 4d), the variation amplitude remains essentially constant for the strongly tilted case, whereas it is slightly increased for the 15° tilt and significantly increased for the yawed case. The larger variation in the latter case is due to the fact that the wind velocity impacting the turbine is not perpendicular to the rotor, but has a component that goes against the blade movement in the upper part of the rotor and with it in the lower part, leading to a larger variation.

Concerning the unsteady loads, further insights are provided by counting the number of cycles per alternating moment range using the rainflow counting algorithm [16]. The number of cycles for each amplitude of alternating moment exerted on the first, second and last wind turbines of the first line is showed on Fig. 5 and 6 for the edgewise and flapwise component, respectively. Misaligning the first turbine results in a peak at higher values of the alternating

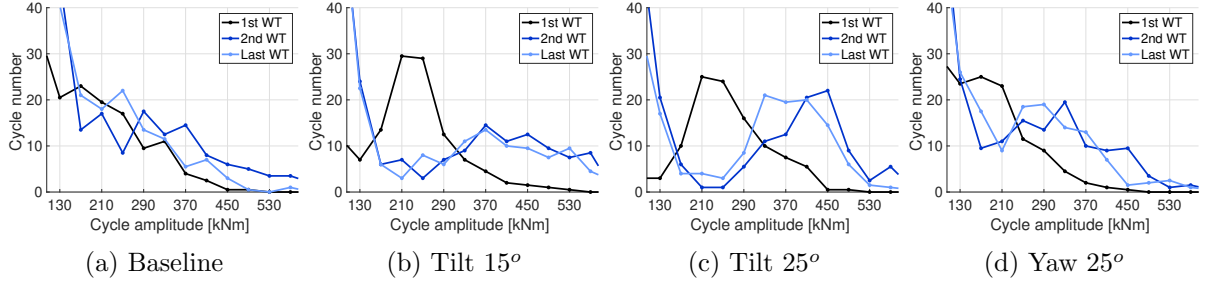


Figure 5: Number of cycles per alternating edgewise moment range for three wind turbines of the first line.

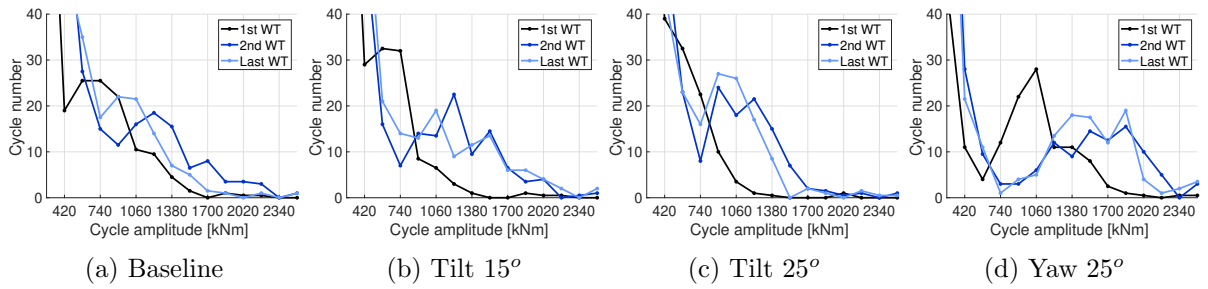


Figure 6: Number of cycles per alternating flapwise moment range for three wind turbines of the first line.

moment compared to the baseline. For tilting, this peak is mostly observable in the edgewise direction, whereas it lies in the flapwise component for the yawed turbines. The peak is shifted towards higher values for the second and last turbines. For the baseline, the shift is limited and is mostly due to the increased level of turbulence and previous wakes meandering. For the misaligned cases, the shift goes to a higher value and is due to the increased asymmetry in the rotor.

The results of the rainflow counting procedure can be summarized into a damage equivalent load (DEL, see [17, 18]) computed by

$$DEL = \left(\sum_{i=0}^{n_c} \frac{n_i M_{a,i}^m}{N_{eq}} \right)^{1/m}$$

where m is the slope of the M-N curve, set to 10 for glass fiber [19], n_i is the number of cycles of alternating moment value $M_{a,i}$ and N_{eq} is the number of equivalent cycles, set to be equal to the number of turbine rotations during the sampled last convective time (560 seconds). The DEL is displayed for the turbines of the first line on Fig. 7.

In general, the DEL significantly increases from the first to the second turbine in all cases, due to the higher level of turbulence and the wake meandering. The baseline case shows a decrease of the DEL amplitude after the third turbine thanks to the homogenization of the flow. On the contrary, it remains constant for the moderately tilted case due to the enhanced wake recovery. The aforementioned decrease of the asymmetry on the rotor in the strongly tilted case moderately reduces the DEL in this case. The latter is also globally lower in the edgewise direction for the yawed case. In the flapwise direction however, it significantly increases for the yawed case, although its evolution as a function of the rotor location remains similar as that observed in the other cases. As a result, the norm of the DEL displayed on Fig. 7c is larger in the yawed case than in the strongly tilted case. Consequently, compared to the baseline case, the

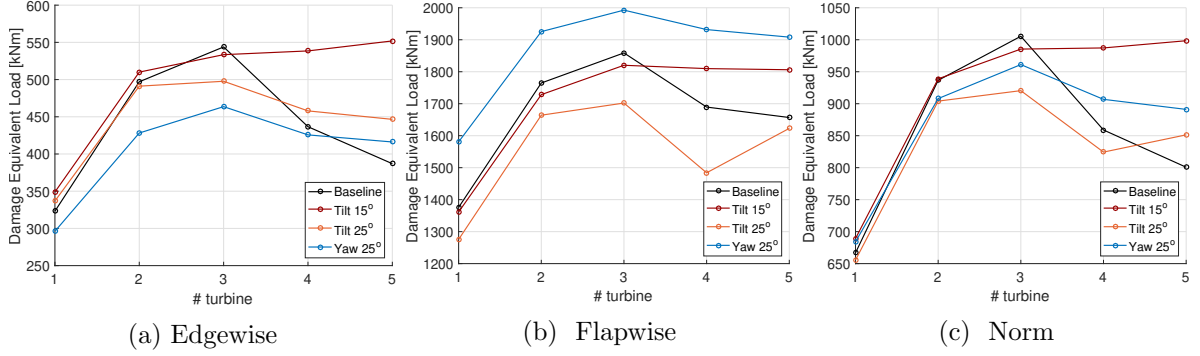


Figure 7: Damage equivalent load of the bending moments exerted on three turbines of the first line.

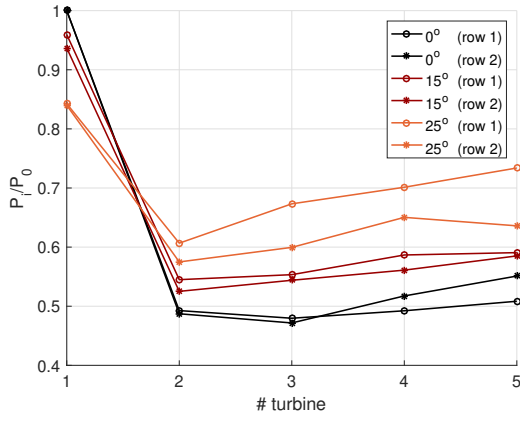


Figure 8: Comparison of the normalized power of the turbines in the tilted cases.

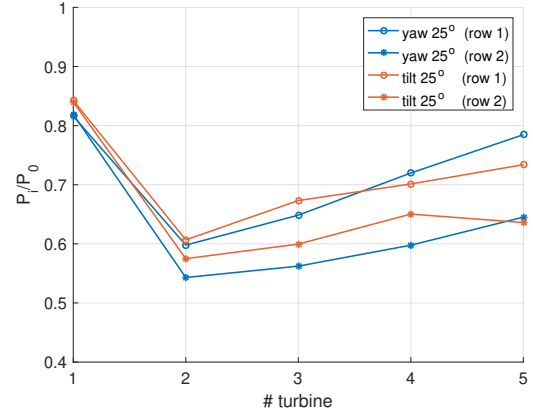


Figure 9: Comparison of the normalized power of the turbines in the strongly tilted and yawed cases.

yawed configuration appears to be more detrimental for the blade structure. On the contrary, the strongly tilted rotors seems to be less damaged, except for the last machine in the line.

3.3. Power

Figure 8 shows the evolution of the power, here normalized by the power of the first wind turbine in the baseline case. The power of the first wind turbine of each line is decreased with the tilt angle. This reduction is 16% in the strongly tilted case and 5% in the moderately tilted case, compared to 18% in the yawed case. However, starting from the second turbine on, the tilted cases produce more power than the baseline. On the last turbine of the first line, the power production was raised by 8% and 23% in the moderately and strongly tilted cases, respectively.

Figure 9 compares the power production of the wind turbines in yaw or tilt configuration. The power output of the three first turbines is more important in the tilted case than in the yawed case. We note that the second line here produces less power for both the yawed and tilted cases. This is due to the fact that the line was impacted by a smaller velocity gust during the ABL simulation.

The power output of the wind farms is summarized in Table 2. Globally, the wake deviation methods generate a significant increase the total power output for the wind farm. The strongly tilted case outperforms the moderately tilted one due to an increased wake deviation.

Interestingly, the case with strong tilt produce 2% more power than the one with strong yaw for the same angle. Therefore, tilting appears to be more efficient than yawing to increase the global power.

Table 2: Total power production.

	Baseline	Moderately tilted (15°)	Strongly tilted (25°)	Strongly yawed (25°)
Total Power [MW]	22.1	23.5 (+6.5%)	25.3 (+14.5%)	24.8 (+12.5%)

4. Conclusion

An actuator line model was used to assess the effect of tilting wind turbines in an aligned farm configuration. Ten wind turbines were placed in an atmospheric boundary layer generated using a concurrent auxiliary simulation. The impact of the deviation angle on three major characteristics was studied: the resulting farm flow, the steady and unsteady loads and the global power output. It is found that the tilt angle deviated the wake towards the ground in an essentially symmetrical manner, which increases the wake recovery rate; it also entrains beneficial high velocity from the ABL. Lower velocities are however seen near the ground and in between the turbine lines as a consequence to the downwards wake deviation. The total damage equivalent load is increased relatively to the baseline for the moderately tilted turbines, but remains close to the baseline in the strongly tilted case due to a reduced load asymmetry on one rotation. At the same angle, the DEL of the tilted case was also lower than in the yawed case. The power output of the farm containing tilted turbines increases significantly, by 6.5% and 14.5% for the 15° and 25° tilt angle, respectively. This is also 2% more than the farm with 25° yawed turbines. Consequently, the tilted design seems to prevail over the baseline and the yawed one in terms of loads and power extraction.

Acknowledgments

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