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Can the power density of a VAWT farm be increased by using turbines as vortex generators to control the atmospheric boundary layer?

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1 Introduction

Over the next decades, wind energy is set to play a pivotal role in the European energy mix as the continent strives to meet ambitious renewable energy targets and reduce dependence on fossil fuels.

Vertical-axis wind turbines (VAWTs) offer a promising solution, particularly for offshore wind farm applications. VAWT wakes tend to recover faster than those of horizontal-axis wind turbines (HAWTs) [1]. Other studies have shown increased performance resulting from favorable fluid interactions in closely spaced configurations with co- and counter-rotating turbines [2, 3, 4]. This characteristic allows for high power density VAWT installations.

In farm configurations, wake losses continue to significantly impact the overall efficiency of the farm. To address this, one may consider implementing a wake steering strategy. The latter involves intentionally operating selected turbines in off-design conditions to deflect their wake away from downstream rotors, thereby improving the overall performance of the wind farm [5].

In the context of vertical-axis wind turbines, Huang et al [6] experimentally demonstrated that modifying the load distribution through fixed blade pitch angles deforms and deflects the wake by generating counter-rotating vortices depending on the pitch setting [7]. The wake deflection was found to be more pronounced with inward blade pitch angles, resulting in a significant increase in available power for potential downstream rotors. Building on this deflection capability, and inspired by Bensason and al. [8] while considering the proximity to the ground, one might ask: could VAWTs be utilized as large-scale vortex generators to create farm-scale vortices and enhance power density?

In the present study, Large-Eddy Simulations (LES) of VAWT farms in a neutral atmospheric boundary layer (ABL) are performed in order to investigate the potential of wake steering to increase the power density of the farm. By combining different directions of rotation, and thus different wake deflections, it is expected to generate farm-scale secondary motions so as to induce a downward advection of high velocity air and therefore improve wake mixing and recovery within the farm. Various combinations of rotation and pitch settings are investigated to assess the efficiency of those strategies and the potential power density increase.

2 Methodology

The simulations of the wind farms are performed using an in-house fourth-order finite difference incompressible LES flow solver [9]. The vertical axis wind turbines are modeled using Actuator Cylinders (AC) supplemented with basic torque controller maximizing power generation according to the blade pitch setting (see Figure (1)) where an inward setting is denoted by a positive ϕ angle. A neutral atmospheric boundary layer inflow is obtained in a concurrent approach using a precursor periodic half-channel flow driven by a pressure gradient. A wall model is used at the bottom and a no through-flow condition is imposed at the top boundary.

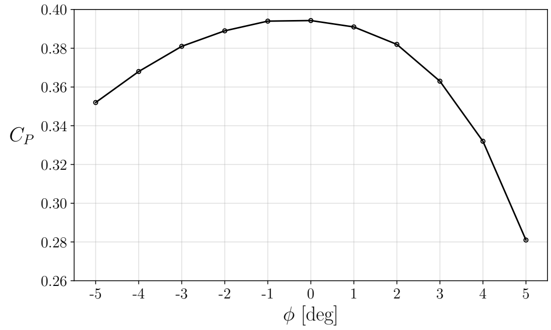

Figure 1. Maximal C_P vs. blade pitch angle ϕ

The wind turbines of the farm are arranged in a grid layout aligned with the mean flow direction (x) and periodic in the transverse direction (z), effectively making the farm infinitely wide. All the turbines have the same blade pitch setting, which is constant along a revolution, and in each streamwise line of the farm, the VAWTs have the same direction of rotation. In the present study, various inward pitch settings and various patterns of alternating directions of rotation are investigated in order to induce lateral deflections of the wake and to generate farm-scale secondary motions.

The ability of those secondary motions to increase the mixing within the ABL and to induce a vertical momentum flux from higher-energy layers toward the center of the farm is investigated. The resulting farm power densities, i.e. mean power divided by the wind farm area, are then evaluated and compared to the reference case with a 0° pitch setting and the same direction of rotation for all the turbines in the farm.

3 Preliminary results

In preliminary investigations, we compared the total power production of 4-by-4 wind farms, with and without an inward fixed blade pitch angle, within a turbulent wind reaching 11 m/s and a turbulent intensity of 6% at mid-span. This analysis was conducted for a specific farm layout with inter-turbine spacings of 10 diameters (D) in the x-direction and 4D in the z-direction. This first layout was not specifically optimized for maximum power density. The VAWTs used in the simulations have a blade span of 138 meters and a diameter of 92 meters. Note that this VAWT geometry is larger than the existing ones; it is chosen to have an influence on the ABL. The VAWTs are positioned such that the lowest part of their blades is located 21 meters above the bottom boundary. The simulation domain is 56D long, 16D wide and 8D high, with uniform horizontal discretization of 16 grid points per diameter and vertical stretching to capture the flow near the ground and around the VAWTs.

Figure 2 illustrates the time-averaged streamwise velocity field at mid-span for two cases: no blade pitch, i.e. 0°, and a 4° inward blade pitch common to every VAWTs. The VAWTS in the two upper lines rotate counter-clockwise, whereas those in the lower lines rotate clockwise. The figure highlights the influence of the blade pitch setting as well as the increasing wake deflection as the flow progresses through the farm.

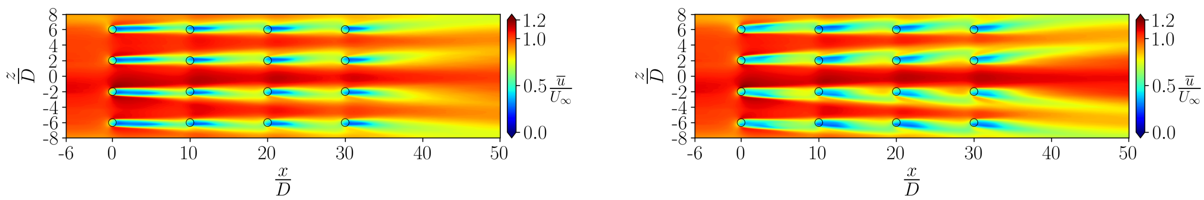

Figure 2: Time-averaged normalized x-component of the velocity field $\frac{\bar{u}}{U_\infty}$ on a horizontal plane a mid-span for two pitch settings: (Left) 0° pitch angle (Right) 4° inward pitch angle.

In the case of the wind farm with 4° pitched blades, we observed the formation of secondary flows, as shown in Figure 3, which are responsible for the vertical downward advection of momentum in the middle of the farm. However, this influx of streamwise momentum from higher-energy layers of the ABL is insufficient to compensate for the individual power losses on each turbine caused by the increased blade pitch angle. As a result, the overall power output is not higher than in the case with 0° blade pitch.

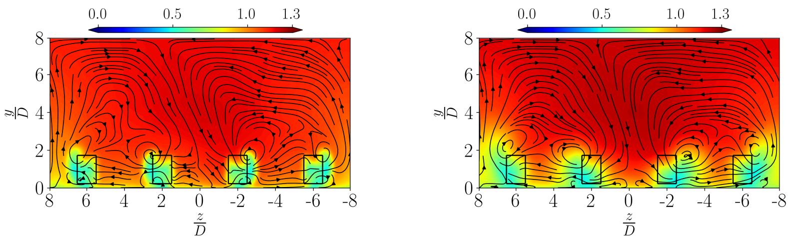

Figure 3: Time-averaged normalized x-component of the velocity field $\frac{\bar{u}}{U_\infty}$ of the 4° pitch angle farm on cross-stream section (Left) 5 diameters (Right) 25 diameters behind the first row.

4 Conclusion

In this preliminary study, the generation of farm-scale secondary motions demonstrates some flow control capability of a wind turbine array and the generation of a downward momentum flux within the farm. However, total power production does not increase for VAWTs with pitched blades. Indeed, the interspace between turbines in the x direction in this initial layout is quite large, i.e. 10D, and the downstream turbines are impacted by wakes with a low speed deficit, even in the case with 0° pitch. The power gain for those turbines when the flow is controlled is, therefore, small or even zero. An arrangement with a higher power density could lead to higher power gains for VAWTs with pitched blades.

For the final results in the presentation, a more refined approach will be used to define the reference layout. A reference case will be established by determining the inter-turbine spacing in both the x and z directions to maximize the power density of a VAWT wind farm with zero blade pitch and the same direction of rotation for all the turbines. Various inward pitch settings and various patterns of directions of rotation for each line will then be investigated in order to assess the potential of wake steering to increase the power density of the farm. Furthermore, a larger layout featuring more than 16 VAWTs could be explored, offering a more accurate representation of real-world offshore wind farms and enabling more comprehensive evaluations of power generation and wake interactions under operational conditions.

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