Large-eddy simulation study of multi-rotor wind turbines

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Abstract. A novel wind turbine configuration comprising of four identical rotors mounted on a single tower is studied using large-eddy simulation (LES) with turbine forces modeled using an actuator drag-disk model. The characteristics of the wakes of the multi-rotor turbine are compared to those of the wake of a conventional turbine comprised of a single rotor per tower. The single-rotor turbine has twice the diameter and the same thrust coefficient as the rotors of the multi-rotor turbine. Several multi-rotor configurations, with varying horizontal and vertical spacings between the four rotors, are evaluated. The multi-rotor turbine wakes are found to recover faster, while the turbulence intensity in the wake is smaller, compared to the wake of the conventional turbine. The mean velocity profiles obtained from the LES results are predicted accurately by a semi-analytical model assuming Gaussian radial profiles of the velocity deficits, and either linear or quadratic superposition of multiple wakes. The classical Jensen wake model, assuming top-hat radial profiles, with quadratic superposition of wakes is also found to accurately predict the decay of the axial mean velocity in the streamwise direction. The interaction between multiple multi-rotor turbines is contrasted with that between multiple single-rotor turbines by considering wind farms with five turbine units aligned perfectly with each other and the wind direction and separated by four single-rotor diameters. The wake losses are found to be significantly smaller in such a wind farm comprising of multi-rotor turbines as compared to single-rotor turbines. The top-hat analytical model is employed to quantify the benefits of the multi-rotor configuration over the conventional single-rotor configuration for a wide range of thrust coefficients and axial spacings. These results suggest that a larger planform energy flux can be achieved without significantly increased fatigue loads by using multi-rotor turbines instead of conventional, single-rotor turbines.

1. Introduction

Wind energy is among the fastest growing renewable sources of energy worldwide. An improved understanding of wind turbine wake interactions is critical to mitigate the deleterious effects of interactions between wakes of multiple turbines. These wake interactions can limit the planform energy flux. The turbulent wake interactions also determine fatigue loads, which impact the levelized cost of energy. Previous work has shown that wake losses are closely tied to wind farm layout parameters such as inter-turbine spacing \cite{1}, alignment between columns and the wind direction \cite{2}, and horizontal and vertical staggering \cite{3}. Configurations involving multiple rotors per tower have been studied previously, by e.g. \cite{4}, and have found benefits with respect to wake recovery but accompanied with increased turbulence. This was because the rotors were concentric and spaced only a fraction of a diameter apart in the axial direction.
In this paper, large-eddy simulations (LES) are conducted to study a novel configuration involving four rotors with identical diameters, \( d \), mounted on a single tower with height \( H_T \) (Figure 1(b)). The tips of the rotors are separated by \( s_h \) and \( s_v \) in the horizontal and vertical, respectively. As a result, the rotors are centered at \( H_T \pm (s_v + d)/2 \), and the mean hub-height is \( H_T \). The multi-rotor configuration (henceforth referred to as 4-rotor turbine) is compared to a conventional turbine with a single rotor (referred to as 1-rotor turbine) with diameter \( D = 2d \) per tower with height \( H_T \) (Figure 1(a)). The total frontal rotor area is \( \pi D^2/4 \) in each case.

The primary benefit of a multi-rotor configuration is the much-reduced weight of blades as compared to a single larger rotor with equal swept area. This is because the weight of the rotor scales as the cube of the diameter, while the swept area increases as the square [5]. A disadvantage is the need for a more complicated tower and support structure [6]. A few recent studies have focused on structural and aerodynamic aspects of multi-rotor turbines [6, 7]. In this paper, we study the benefits associated with the wakes of multi-rotor turbines. We show that the multi-rotor turbine wakes recover faster compared to wakes of an equivalent single-rotor turbine. The turbulent kinetic energy added due to multi-rotor turbines is also lesser than that due to an equivalent single-rotor turbine. We show that this leads to reduced wake losses, as well as potentially smaller fatigue loads, in wind farms comprised of multi-rotor turbines.

2. Numerical and analytical model framework

2.1. Governing equations and numerical methodology

The standard LES-filtered incompressible Navier-Stokes equations are solved on a structured uniform Cartesian mesh using Fourier-collocation in \( x \) and \( y \) directions, sixth-order staggered compact finite-differences in the \( z \) direction and a total variation diminishing (TVD) fourth-order Runge-Kutta time-stepping scheme. Non-periodicity is imposed in the \( x \) direction using a fringe region technique [8]. Partial dealiasing is achieved by applying the standard 2/3 rule in \( x, y \) and the use of skew-symmetric form for the convective terms in the \( z \) direction. The effect of sub-filter scales is modeled using the Sigma model [9] with a coefficient \( C_\sigma = 1.3 \). Wind turbine forces are modeled as momentum sinks using the actuator drag-disk model [10]. Algebraic wall models based on the Monin-Obukhov similarity theory are used to specify the shear stresses at the bottom wall. Subgrid-scale stresses in the rest of the domain are smaller than the sub-filter scale stresses by around 8-10 orders of magnitude and, hence, are neglected in these simulations. The code has been validated over several previously published studies [11, 12, 13].

2.2. Setup and cases simulated

Half-channel (HC) simulations are carried out using the concurrent precursor-simulation methodology [14] on domains \( (L_x, L_y, L_z) = (\pi \times \pi/2 \times 1) H \), where \( H \) is the height of the
half-channel, driven by a constant imposed pressure gradient, $-u_*^2/H$, where $u_*$ is the friction velocity at the bottom wall. The HC configuration is used as a model for the neutrally-stratified atmospheric boundary layer (ABL) with the Coriolis forces neglected [2, 10], and we use the terms HC and ABL interchangeably. The surface roughness height at the bottom wall is $z_0 = 10^{-4}H$. This corresponds to rough land, and has been used in previous wind turbine studies [10]. The turbulence intensity at a typical hub height of $0.1H$ is approximately 8%. All results are normalized using scales $H$ and $u_*$, with typical values $H = 1000$ m, $u_* = 0.45$ m/s.

ABL simulations (without turbines and with streamwise periodicity) are carried out first for 100 time units (1 time unit $= H/u_*$), so as to achieve a fully-developed statistically stationary state on a grid with $192 \times 96 \times 128$ points. The velocity fields are then up/down sampled to the desired final grid size, and are used to initialize the ‘precursor’ and ‘main’ simulation domains. Turbines are introduced in the ‘main’ domain, and the last three-quarters of this domain is forced with the velocity field from the ‘precursor’ domain at each time step. Simulations in this concurrent precursor-simulation mode are carried out for a further 20 time units, with time-averaging performed over the last 8 time units.

Isolated turbine simulations are carried out for a baseline 1-rotor configuration with $D = 0.1H$, and a baseline 4-rotor configuration with $d = s_h = s_v = 0.05H$. Three additional isolated 4-rotor turbine simulations are carried out with varying $s_h$ and $s_v$ to study the effect of spacings in the 4-rotor configuration. Finally, a line of five 1-rotor turbines separated by a distance $4D$ in the streamwise direction is compared to a similar configuration with a line of five 4-rotor turbines separated by $4D$ in the streamwise direction. All isolated turbines, and the most upstream turbine in the five-turbine cases, are located at $x = 0$, where the domain inlet is at $x = -4D$. All turbines are located at $y = Ly/2$ in the spanwise direction and the tower height is $H_T = 0.1H$ for all turbines. The effective simulation domain, which is not affected by the fringe region used to enforce non-periodicity, extends for approximately $24D$ in the streamwise direction. The thrust coefficient $C_T = 0.75$ is used for all rotors.

### 2.3. Analytical models

Two analytical wake modeling frameworks are used in this paper. Both models assume the wake decays in the streamwise $(x)$ direction. The classical wake model by [15] assumes that the wake follows a top-hat profile in the radial $(y-z)$ directions. A newer model by [16] assumes a Gaussian radial profile for the wake. The deficit due to turbine rotor $i$ located at $(x_i, y_i, z_i)$ at a downstream point $(x, y, z)$ is given by the top-hat model as

$$
\frac{\Delta \bar{u}_i(x, y, z)}{\bar{u}_{ap}(z)} = \frac{1 - \sqrt{1 - C_T}}{[1 + 2k_w(x - x_i)/d_0]^{1/2}},
$$

(1)

for $x > x_i$ and $(y - y_i)^2 + (z - z_i)^2 \leq [d_0/2 + k_w(x - x_i)]^2$. The deficit prediction by the Gaussian model is

$$
\frac{\Delta \bar{u}_i(x, y, z)}{\bar{u}_{ap}(z)} = \left(1 - \sqrt{1 - \frac{C_T}{8(k^* (x - x_i)/d_0 + \epsilon \sqrt{\beta})^2}}\right) \times \exp \left(-\frac{(y - y_i)^2 + (z - z_i)^2}{2(k^* (x - x_i) + \epsilon \sqrt{\beta} d_0)^2}\right),
$$

(2)

for $x > x_i$, where $\beta = [1 + \sqrt{1 - C_T}]/[2\sqrt{1 - C_T}]$, $d_0 = D$ for 1-rotor and $d$ for 4-rotor cases. The argument of the square-root in the first bracket on the right-hand side of Eq. (2) is set to zero whenever it is less than zero, which happens very close to the turbines. The mean velocity at each point in the domain is calculated according to

$$
\bar{u}(x, y, z) = \bar{u}_{ap}(z) - \Delta \bar{u}_{tot}(x, y, z); \quad \Delta \bar{u}_{tot}(x, y, z) = \left[\sum_i \Delta \bar{u}_i^p\right]^{1/p}.
$$

(3)
The parameter \( p \) controls the manner in which multiple wakes merge. Linear addition of wake momentum deficits is obtained by setting \( p = 1 \), while an addition of kinetic energy deficits is implied by \( p = 2 \). The upstream velocity is assumed to follow the logarithmic profile, \( \bar{u}_{up}(z) = \left( \frac{u_*}{\kappa} \right) \ln\left( \frac{z}{z_0} \right) \), with \( \kappa = 0.4 \). For an isolated 1-rotor case, the top-hat model involves one empirical parameter, \( k_w \), while the Gaussian model involves two empirical parameters, \( k^* \) and \( \epsilon \). \( p \) is an additional empirical parameter for cases involving an isolated 4-rotor turbine or multiple 1-rotor or 4-rotor turbines. Following [15], we use \( p = 2 \) with the top-hat model. We evaluate both choices, \( p = 1, 2 \), with the Gaussian model.

3. Results

3.1. Baseline cases

Instantaneous contours of streamwise velocity for the baseline cases are shown in Fig. 2. Features of the turbulent wakes and the ABL at the mid-span planes and at planes a short distance behind the turbines can be seen in Fig. 2.

Results of an isolated 1-rotor turbine are shown in Fig. 3. Vertical profiles in the mid-span plane \((y = Ly/2)\) for several locations downstream of the turbine are shown in Fig. 3(a-b). Streamwise profiles of disk-averaged quantities are shown in Fig. 3(c-d). The disk-averages are computed by integrating over a circle in the \( y-z \) plane centered at \((Ly/2, 0.1H)\) and with a diameter \( D \). The velocity deficits follow a near-Gaussian shape in the radial direction, and decrease with increasing axial distance, as the wake recovers. The Gaussian analytical model with \((k^*, \epsilon) = (0.03, 0.2)\) is seen to reproduce radial and axial variations of the mean velocity deficits obtained from the LES quite accurately. The top-hat model with \( k_w = 0.0579 \) does
Figure 3. Results of isolated 1-rotor turbine. (a) Mean streamwise velocity deficits at the centerline, $\Delta U(x, z) = U(x, Ly/2, z) - U(-1D, Ly/2, z)$. (b) Added turbulent kinetic energy at the centerline, $\Delta TKE(x, z) = TKE(x, Ly/2, z) - TKE(-1D, Ly/2, z)$. Disk-averaged (c) streamwise velocity deficit and (d) added TKE. For any $q$, $q_{disk} = (4/\pi D^2) \int_{disk} q dA$, with the integral carried out over one disk of diameter $D$. (a,c) Top-hat model used $k = 0.0579$ and Gaussian wake model used $(k^*, \epsilon) = (0.03, 0.2)$.

not predict the radial profile correctly, but predicts the disk-averaged velocity quite accurately. The added TKE is maximum close to the top of the turbine rotor disk (at $z = 0.15H$) and approximately $4D$ downstream in the axial direction. These observations are consistent with previous studies on isolated turbines [17].

Fig. 3 shows that the mean velocity profiles are well-converged on the $192 \times 96 \times 128$ grid. The TKE profiles are also quite well-converged, except very close to the peaks in the $x$ and $z$ directions. We conclude that this grid size is sufficient for the 1-rotor cases for the present purposes, and the 5-turbine 1-rotor simulation is carried out using this grid.

Results of the baseline isolated 4-rotor case are shown in Fig. 4. Vertical profiles at one of the spanwise center-planes ($y = Ly/2 - d$) are shown in Fig. 4(a-b). Similar results in the other spanwise center-plane ($y = Ly/2 + d$) are not shown. The disk-averaged quantities shown
Figure 4. Results of isolated 4-rotor turbine. (a) Mean streamwise velocity deficits at the centerline, $\Delta U(x, z) = U(x, Ly/2 - d, z) - U(-1D, Ly/2 - d, z)$. (b) Added turbulent kinetic energy at the centerline, $\Delta TKE(x, z) = TKE(x, Ly/2 - d, z) - TKE(-1D, Ly/2 - d, z)$. Disk-averaged (c) streamwise velocity deficit and (d) added TKE. For any $q$, $q_{disk} = (4/\pi D^2) \int_{disk} q dA$, with the integrals carried out over four disks of diameters $d$ each. (a,c) Top-hat model used $(k_w, p) = (0.0579, 2)$. Gaussian wake model used $\epsilon = 0.18$, $k^* = 0.035$, and $p = 1$ or $2$.

in Fig. 4(c-d) refer to integrals computed over four circles of diameters $d$ each and centers at different $y, z$ locations.

Similar to the baseline 1-rotor case, the Gaussian radial shape of the velocity deficits and recovery of the wake, characterized by the decay of the disk-averaged velocity deficits, are seen. The TKE profiles have four local peaks in the vertical direction very close to the turbine, while the streamwise variation is similar to that in the 1-rotor case. The mean velocity and TKE profiles indicate that a grid of size $256 \times 128 \times 160$ is sufficient for obtaining converged results. All 4-rotor simulations henceforth use grids of sizes $256 \times 128 \times 160$.

The Gaussian model with $p = 1$ is seen to predict the radial profiles very accurately in Fig. 4(a). With $p = 2$, the radial variation of the velocity deficit is under-predicted for larger
The differences between the different 4-rotor cases are small compared to Fig. 5(a). The disk-averaged turbulence intensities are also smaller in the 4-rotor cases compared to the 1-rotor case. The lateral wake interactions to the 1-rotor case ignores the interactions among the individual wakes of the 4-rotor turbine in the lateral directions. Fig. 4(a) suggests that the lateral wake interactions are insignificant for $x/D = 3$, but are significant for $x/D = 6$. Thus, the extent of wake recovery is expected to depend on the horizontal and vertical spacings $s_h$ and $s_v$ in the 4-rotor turbine.

To study the sensitivity to spacings $s_h$ and $s_v$, the baseline 1-rotor and 4-rotor cases are supplemented with three additional 4-rotor cases. These additional 4-rotor cases have differing horizontal and vertical spacings, $(s_h, s_v) = (2d, 1d)$, $(1d, 0d)$, and $(1d, 2d)$. The disk-averages of velocity are significantly smaller in the 1-rotor case compared to all the 4-rotor cases, as seen in Fig. 5(a). The disk-averaged turbulence intensities are also smaller in the 4-rotor cases compared to the 1-rotor case. The differences between the different 4-rotor cases are small compared to $x/D$. However, we note that the under-prediction is small, as the horizontal scale has reduced significantly between leftmost and the rightmost panels in Fig. 4(a). Fig. 4(c) shows that the Gaussian model with both, $p = 1$ and $p = 2$, represent the streamwise variation of the disk-averaged deficits quite accurately. Similar to the 1-rotor case, the top-hat model predicts the disk-averaged velocities accurately, although the shape in the radial direction is incorrectly predicted.

Comparing Fig. 3(c) to Fig. 4(c), it is clear that the velocity deficit is significantly smaller in the 4-rotor case compared to the 1-rotor case at each downstream $x/D$. This indicates that the combined wake of the 4-rotor turbine recovers faster. This is because the wakes of each of the individual rotors in the 4-rotor turbine have a characteristic length scale $d = D/2$. These individual wakes, thus, recover with a characteristic length $d$, while the wake of the 1-rotor turbine recovers with a characteristic length $D$. In other words, a downstream distance of, e.g. $4D$, is effectively 8 diameters ($8d$) downstream from the turbine for the individual wakes of the 4-rotor turbines. The faster recover may also be anticipated by noting that the ratio of the total perimeter of the rotor-disk to the frontal area for the 4-rotor turbine ($4/D$) is twice that for the 1-rotor turbine ($4/D$). The larger perimeter per frontal area allows for larger entrainment and faster recovery of the wake, especially in the near-wake region.

3.2. Effect of $s_h$ and $s_v$

The above picture explaining the faster wake recovery in the baseline 4-rotor case compared to the baseline 1-rotor case ignores the interactions among the individual wakes of the 4-rotor turbine in the lateral directions. Fig. 4(a) suggests that the lateral wake interactions are insignificant for $x/D = 3$, but are significant for $x/D = 6$. Thus, the extent of wake recovery is expected to depend on the horizontal and vertical spacings $s_h$ and $s_v$ in the 4-rotor turbine.
3.3. Multiple turbine cases

Fig. 5 show the potential benefits of the 4-rotor configuration over the 1-rotor configuration. For example the velocity recovers to about 85% of its upstream value at a distance $x = 4D$ in the 4-rotor cases as against to only 65% in the 1-rotor case. As a result, a wind farm comprising of multiple aligned 4-rotor turbines would experience smaller wake losses compared to a wind farm comprising of multiple 1-rotor turbines with identical streamwise spacing. Note that the streamwise distances are always normalized by the 1-rotor turbine diameter, $D$. Fig 5(b) shows that the turbulent fluctuations, and as a result fatigue loads, experienced by the downstream turbines in a 4-rotor wind farm would be smaller than those in a 1-rotor wind farm with identical spacing.

To verify these observations, two additional simulations are carried out. The first comprises of five identical 1-rotor turbines aligned with each other, with a streamwise spacing of 4D. The second simulation considers an identical layout of five 4-rotor turbines with $s_h = s_v = d$. The turbines are located at $x/D = 0, 4, 8, 12, 16$. Disk averages of velocity deficits and added TKE, calculated as for the isolated turbine cases, are shown in Fig. 6.

Due to the perfect alignment between the turbines and the wind direction, strong interaction between the wakes of the upstream and downstream turbines is seen in Fig. 6. Similar to the
isolated turbine cases, the velocity deficits (Figs. 6(a-b)) and the added TKE values (Fig. 6(c)) are smaller for the 4-rotor wind farm compared to the 1-rotor wind farm.

The velocity deficits jump from zero upstream of the first turbine and attain an asymptotic value. Figs. 6(a-b) show that the Gaussian model predictions with $p = 1$ are inaccurate beyond the first turbine, since the velocity deficits continue to accumulate with each successive downstream turbine. On the other hand, Gaussian model predictions with $p = 2$ show the correct qualitative behavior, since the deficits almost saturate at the second turbine. The model predictions with $p = 2$ are in reasonable agreement with the LES results. The top-hat model results are also in reasonable agreement with the LES results.

Fig. 6(d) quantifies the power generated by turbines relative to the power generated by the LES in the two wind farm simulations. The relative power of turbine $i$ from the LES is computed as $\langle u_i^3 \rangle / \langle u_i^3 \rangle$, where $u_i$ denotes the instantaneous velocity averaged over the disk(s) of turbine $i$, and $\langle \rangle$ denotes the time-average of the $q$. The relative power of turbine $i$ from the wake models is computed as $\bar{u}_i^3/\bar{u}_i^3$, where $\bar{u}_i$ is the velocity predicted by the model averaged over the disk(s) of turbine $i$. The top-hat model predictions are seen to be in reasonable agreement with the LES results in Fig. 6(d). The broad features of the wake losses in the second through fifth turbines are captured correctly, except for a large over-prediction in the 1-rotor case for the second turbine and a small over-prediction in the 4-rotor case for the fifth turbine. The Gaussian model results are seen to be qualitatively similar to the top-hat model results, but are seen to under-predict most of the LES results.

### 3.4. Effect of thrust coefficient and turbine spacing

All the LES results shown in this paper have assumed a constant thrust coefficient ($C_T = 0.75$) for all rotors. Also, only one inter-turbine spacing ($S_X = 4D$) was considered in the multiple-turbine cases. The sensitivity to $C_T$ and $S_X$ is investigated here using the top-hat model with parameters $(k_w, p) = (0.0579, 2)$. It should be mentioned that the results in this sub-section are based on the rather strong assumption that $k_w = 0.0579$ is appropriate for all combinations of $C_T$ and $S_X$. The relative power of the fifth turbine, predicted by the top-hat model, is plotted in Fig. 7(a-b) for 1-rotor and 4-rotor wind farms, respectively. We focus on the fifth turbine as it is representative of a turbine in the asymptotic region, since the wake losses have usually saturated by the fifth row [2].

Fig. 7(a) shows that, for a 1-rotor wind farm, the relative power of the fifth turbine decreases with increasing $C_T$ for a fixed $S_X$, as well as with decreasing $S_X$ for a fixed $C_T$. A similar behavior of the relative power is seen in the case of 4-rotor wind farms in Fig. 7(b). Fig. 7(c)
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shows that the wake losses are smaller for the 4-rotor wind farm as compared to the 1-rotor wind farm for all combinations of $C_T$ and $S_X$. The benefit offered by the 4-rotor turbines over 1-rotor turbines reduces as the turbine spacing increases and as the thrust coefficient decreases.

4. Conclusions and further work
A combined LES and analytical modeling study of the novel 4-rotor wind turbine configuration has been carried out. The 4-rotor wind turbine is shown to lead to faster wake recovery compared to the conventional 1-rotor configuration. This is due to the ratio of the wake perimeter to the frontal area being twice in the 4-rotor configuration, which allows for greater entrainment. The enhanced wake recovery is systematically, but weakly, dependent on the horizontal and vertical spacings between the individual rotors of the 4-rotor turbine. Arranged as a line of turbines perfectly aligned with the wind direction, the 4-rotor configuration shows benefits from faster wake recovery as well as reduced TKE, with the potential for reduced fatigue loads. The 4-rotor turbines are particularly beneficial when multiple units are packed relatively close to each other, and when the operating thrust coefficient is large.

Several aspects of this problem need further study. A detailed analysis of the mean and TKE budgets should be carried out to deduce the physical mechanisms that contribute to the faster wake recovery and reduced turbulence intensity in the 4-rotor turbine cases with respect to the 1-rotor turbine case. The number of LES cases needs to be expanded to cover larger variations of thrust coefficient and axial spacing. The instantaneous loads experienced at the individual rotor centers and the structure as a whole in the 4-rotor configuration should be analyzed. Studies using the actuator-line technique, which provides a more accurate description of the very near-wake region should be carried out. Actuator-line simulations would also enable study of control strategies such as counter-rotation and phase-locking of different rotors in the multi-rotor turbines. Finally, larger wind farms in aligned and staggered arrangements, and hybrid wind farms, comprising of a mixture of 1-rotor and 4-rotor configurations can be studied.

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