A comparative study of wake interactions between wind-aligned and yawed wind turbines using LES and actuator line models

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Abstract. An LES based OpenFOAM solver is coupled with the actuator line model for the simulation of wind farms and the prediction of power production. The tool developed is validated for wind aligned and yawed tandem wind turbines. Two NREL 5MW turbines in a tandem configuration are considered. The solution parameters are first studied in detail. The development of vortical wakes behind the upstream and the downstream turbines are simulated under uniform and atmospheric boundary layer inflow conditions, and the power productions of the turbines are predicted. The impact of a yawed upstream rotor on its wake deflection and the resulting power production of the tandem configuration are assessed. It is shown that the coupled solver developed is quite successful in capturing the wake deficits and wake deflections, and predicting the power production of tandem wind turbine configurations.

1. Introduction
Wind energy has become one of the most utilized renewable energy sources in the past decades. Wind farms consist of many wind turbines, working under ever-changing atmospheric conditions over complex terrains. Increasing the overall efficiency of a wind farm has always been a complex problem due to many parameters that simultaneously affect the power output. One of the most critical factors in the micro-siting of a wind farm is the wake. Not only wake generated by the upstream turbines can cause an overall power deficit of up to 20% compared to a hypothetical no-wake scenario [1], it has other negative effects such as fatigue loading on rotor structures. Since it is an unavoidable result of energy extraction from the wind, diminishing its effect has been and still is an active research area. The most obvious method is to reduce every rotor’s exposure to the wake as much as possible. Placing each turbine at a certain lateral offset of the closest upstream turbine’s wake region in terms of the dominant wind direction is a common practice. Some counter-intuitive approaches are also available, such as curtailing the upstream turbines purposely to lessen its impact on downstream turbines so that overall power is increased [2]. Wake effect is also very sensitive to wind speed and direction, as well as atmospheric turbulence levels, which is the primary factor in the rate of wake recovery. Situation-specific actions should be taken in off-design conditions, among which deflecting the wake by tilting or yawing the rotors are the most practical.

Computational methods offer good potential in simulating the aforementioned multi-parameter problems. Many simplified wake models have been developed and are still in use today, such as analytical models [3][4] or free-vortex methods [5]. On the other hand, it is possible to
carry out a full Navier-Stokes solution of a complete wind farm with today’s computer technology. Nevertheless, it is mostly not practical with a common computing system due to the wide range of length and time scales that are required to be resolved: from millimeters over the blade boundary layer to kilometers of bulk wind flow over the terrain. Also, additional treatment is needed for the rotational motion of blades; such as multi-reference frames, sliding mesh interfaces or over-set grids. Actuator models have emerged as a remedy to such complexities; resolving the boundary layer scale flow is avoided by replacing physical blade boundaries by body forces, which is also easy to rotate without additional treatment.

Despite different approaches, such as actuator disk or line models, the primary goal of actuator models, in general, is to compute the wake accurately with some less computational cost at the expense of a detailed flow solution in the blade vicinity. The actuator line model was first introduced by Sorensen and Shen [6], which offers detailed blade tip vortex shedding and performs better for unsteady simulations, thus yielding higher fidelity results compared to the actuator disk model. The actuator line model is shown to be very sensitive to simulation parameters (such as force projection parameter, grid resolution, and time step size) and numerous fine-adjustment studies have been carried out. According to Martinez-Tossas et al. [7], not only the optimum projection width depends on the shape of the airfoil profile, but it should also be within a certain percentage of the chord length. Jha et al. [8] have studied the Gaussian projection parameter in detail and suggested a transformed chord based distribution in the form of an elliptic wing that fits the turbine blade geometry. Shen et al. [9] have shown that the actuator line model was capable of capturing the variations in force distribution along the blades at different yaw angles accurately. Baratchi et al. [10] have simulated a single wind turbine at various tip speed ratios and yaw angles using both actuator line and blade element based actuator disk models. They have concluded that the actuator line model is better at capturing tip vortices and unsteady wake structures.

In this study, the NREL 5MW wind turbine is modeled in single and multiple rotor configurations using the actuator line model within OpenFOAM. In LES solutions, simulation parameters are finely tuned on an isolated rotor with respect to the estimated power production at different tip speed ratios. Then, wake interactions between two wind turbines in a tandem configuration are simulated for wind-aligned and yawed upstream rotor cases. Wake deflection and its effect on power production are assessed.

2. Methodology

The methodology employed has two core modules: the turbulent flow solver and the turbine model. The unsteady, incompressible Navier-Stokes equations are discretized and solved by OpenFOAM’s [11] respective flow solver: pimpleFoam. Turbulence is modeled using Large Eddy Simulation (LES) approach. Turbine blades are introduced into the flow domain using the actuator line model (ALM). The ALM implementation is based on an OpenFOAM library extension, turbinesFoam [12], which is slightly modified and corrected in the present study. Spatial discretization (generation of the grid) is performed also by using built-in OpenFOAM tools. Validation and verification of power production at different tip speed ratios are based mainly on the Blade Element-Momentum (BEM) theory. Both ALM and BEM requires pre-calculated aerodynamic loads, $c_l$ and $c_d$ data. These coefficients are obtained via the well-known low Reynolds number airfoil analysis tool, XFOIL [13]. The BEM predictions are obtained by one of the most widely used and validated tool QBlade [14].

2.1. Flow solver: OpenFOAM

OpenFOAM is an open source toolbox that includes flow solvers suitable for various flow cases, as well as a basic level grid generator. It incorporates the finite volume approach for the discretization of partial differential equations and also may be executed in parallel. In this study,
OpenFOAM’s unsteady flow solver for incompressible flows, pimpleFoam, is used. pimpleFoam derives its name from the combination of PISO (Pressure Implicit with Splitting of Operator) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithms. Incompressible flow assumption is made due to the fact that the highest velocity magnitude in simulations (which is linear tip speed of the blades) does not exceed $Mach = 0.3$.

\[
\nabla \cdot \tilde{\mathbf{u}} = 0 \tag{1}
\]

\[
\frac{\partial}{\partial t} \tilde{\mathbf{u}} + (\tilde{\mathbf{u}} \cdot \nabla)\tilde{\mathbf{u}} = -\nabla \tilde{p} + \nu \nabla^2 \tilde{\mathbf{u}} - \nabla \cdot \tilde{\tau}^d + \tilde{f}_b \tag{2}
\]

\[
\tau_{ij}^d = \tau_{ij} - \frac{1}{3} \delta_{ij} \tau_{kk} \tag{3}
\]

\[
\tau_{ij}^d = -2\nu_{SGS} S_{ij} \tag{4}
\]

\[
\nu_{SGS} = (C_S \Delta)^2 |S| \tag{5}
\]

\[
S = \frac{1}{2} (\tilde{u}_{j,i} + \tilde{u}_{i,j}) \tag{6}
\]

\[
|S| = \sqrt{(2S_{ij}S_{ij})} \tag{7}
\]

Turbulence is modeled using Large Eddy Simulation (LES) approach, in which large-scale eddies are resolved by the Navier-Stokes equations (Eq. 1-3), where the curly over-bar symbol represents the resolved quantities. Here, $\tau_{ij}^d$ is the sub-grid scale stress tensor, $\nu_{SGS}$ is the sub-grid scale viscosity which needs to be modeled, and $S$ is the rate of strain tensor. $\nu_{SGS}$ is provided by the well-known Smagorinsky model [15] (Eq. 4-7), where $C_S$ is the model constant, $\Delta$ is taken as the cube root of cell dimensions in all directions, i.e. $\Delta = (\Delta_x \Delta_y \Delta_z)^{1/3}$. The Smagorinsky constant [16] is taken as $C_S = 0.168$.

### 2.2. Actuator Line Model (ALM) and Blade Element Momentum (BEM) theory

The actuator line model (ALM) [6] is employed for modeling the turbine blades in the flow field. The sectional aerodynamic forces acting along turbine blades are computed separately and exerted into the flow field as a body force in the conservation of momentum equation (2). It is similar to the Blade Element-Momentum (BEM) theory, which is a simple, widely used yet powerful approach to model a rotor performance (Fig. 1).

In the present study the lift and the drag force coefficients for blade sections are evaluated by XFOIL [13] in advance and tabulated with respect to the angle of attack and Reynolds number. XFOIL is a sub-critical 2D airfoil solver which employs integral boundary layer theory, also capable of predicting separation and transition using the $e^9$ method.

The “pressure leakage” at blade tips is also modeled with a tip correction factor similar to
The BEM methodology. The tip correction factor $F_{\text{loss}}$, which is based on Glauert’s suggestion and further improved by Shen et al. is used in this study [17];

$$F_{\text{loss}} = \frac{2}{\pi} \cos^{-1} \left( \exp \left( -g \frac{N_B (R - r)}{2r \sin \phi} \right) \right)$$  \hspace{1cm} (8)

where $g$ is given as;

$$g = \exp(-0.125(N_B \lambda - 21)) + 0.1$$  \hspace{1cm} (9)

where $N_B$ is the number of blades and $\lambda$ is the tip speed ratio.

The quasi-steady forces are evaluated for each blade element at every time step based on the local flow properties and are exerted into the flow field at the quarter chord locations of the blade elements at their mid-spans, which are known as actuator points. In order to prevent singular behavior and instability in the flow solution, the point force exerted into the flow field is distributed among the cells around the actuator point by a 3D Gaussian distribution function:

$$\eta = \frac{1}{\epsilon^3 \pi^{3/2}} \exp \left( -\left( \frac{|r|}{\epsilon} \right)^2 \right)$$  \hspace{1cm} (10)

where $\epsilon$ is known as the Gaussian kernel and represents the width of the projection sphere which needs to be adjusted. Another ambiguous model-specific parameter in an ALM implementation is the sampling location of the local velocity. In the present study, the actuator point, which is suggested by Sorensen et al. [6], in the original study, is employed.

The coupling between the velocity field and the aerodynamic forces at the actuator points is maintained through the iterative solution algorithm shown in Fig. 2. The outer iterations between the ALM and the pimpleFoam solutions continue until the velocity field at the actuator points converge within a user defined tolerance.

### 2.3. Computational grid and boundary conditions

The solution domain is discretized with a block structured Cartesian grid with different resolutions. OpenFOAM’s built-in blockMesh and snappyHexMesh tools are used for the grid generation. The Cartesian cell sizes start at its coarsest ($\Delta_g = 63m$) at the far-field boundaries and is gradually refined towards the rotor plane, reaching $\Delta_g \approx 8m$. In the vicinity of the rotor plane and in the wake, the grid is further refined according to the desired cell size-to-rotor radius ratio, $\Delta_g/R$. The grid refinement is done by halving the cell sizes in each direction by dividing a single cell into 8 cells.

The solution domain extends from $-3D$ to $20D$ in the flow ($x$) direction, $-3D$ to $3D$ in lateral ($y$) direction and $-90m$ (hub height) to $3D$ in vertical ($z$) direction (Fig. 3). The refinement level at the rotor plane is fixed to $R/\Delta_g = 32$ for all wake interaction simulations. The number
of cells employed is $\approx 6M$. The hub and the turbine tower are not modeled in the present simulations.

At inflow boundaries, an ABL profile is applied using OpenFOAM’s built-in `atmBoundaryLayer` patch type, which is suggested by Hargreaves and Wright [18]. The model assumes $z$ as the vertical coordinate. The axial component of velocity as a function of $z$, $U_x(z)$ is given by Eq. 11, where $U^*$ is the friction velocity, which is related to turbulent kinetic energy and the dissipation rate. Here, $z_0$ is the surface roughness height, which is taken as 0.001m [19] to reflect typical offshore conditions. $\kappa = 0.41$ is the von Karman constant and $C_{\mu} = 0.09$ is the turbulence viscosity coefficient.

$$U_x(z) = \frac{U^*}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right)$$  \hspace{1cm} (11)$$

$$k = \frac{(U^*)^2}{\sqrt{C_{\mu}}}$$  \hspace{1cm} (12)

$$\varepsilon = \frac{(U^*)^3}{\kappa(z + z_0)}$$  \hspace{1cm} (13)

3. Results and discussion

NREL’s 5MW reference wind turbine [20] is used in the validation studies. It is a 3-bladed HAWT with 63m of rotor radius and rated at $U_\infty = 11.4m/s$ with a tip speed ratio of TSR = 7 at $\approx 12.1RPM$. In this study, the rotation direction is set to $+x$ (clock-wise when faced from upstream). First, the critical simulation parameters of the actuator line model are fine-tuned on a single rotor which is isolated from the ground effects. As shown in Fig. 4, the present predictions made on a uniform grid with a cell size, $\Delta_g$ is 1/32 of the rotor radius, Gaussian $\epsilon = 1.25\Delta_g$ and CFL$_{tip}$ $^1$ = 1.80 yield a good agreement with both the BEM predictions and the RANS predictions on a fully-resolved grid [21] for a wide range of tip speed ratios.

Next, two NREL 5MW rotors are placed in a tandem configuration with a separation distance of $7D = 882m$ and two cases are studied. In the first case, the upstream turbine is wind-aligned ($\psi_{WT_1} = 0^\circ$) while in the second case it is yawed by $\psi_{WT_1} = 25^\circ$. The inflow velocity is set to $U_\infty = 8m/s$ at the hub height and the tip speed ratio of both rotors are fixed at $TSR = 7.3$.

3.1. Unsteady wake behind a wind-aligned upstream rotor

When the upstream turbine (WT1) is aligned with the incoming wind, both rotors exhibit a similar wake development until the wake impingement (Fig. 5a). At around $t = 150s$, the wake of WT1 reaches the downstream turbine, and the turbulent wake structures behind WT2 start forming (Fig. 5b). At that instant, a certain asymmetry in the wake of WT1 close to the WT2 can be observed. The slight inclination in $-y$ direction is attributed to the clockwise rotation of the turbines.

The x-plane cuts of vorticity contours (Fig. 6) and Q-criterion iso-surfaces (Fig. 7) show the development of the wake behind the turbines. The helical formation of the blade tip vortices

$^1$ Here, CFL$_{tip}$ is analogous to the CFL number, i.e. the time step size is chosen such that blade tip does not travel more than 1.80 times the cell size in a single time step
stay visible within the 1D downstream of the upstream turbine, whereas the strong turbulent structures emanating from the blade roots stay visible longer. The presence of such wake patterns in the absence of a hub are also reported in the previous studies [10]. As expected, turbulent structures increase dramatically behind the downstream turbine.

3.2. Unsteady wake behind a yawed upstream rotor

The instantaneous velocity and vorticity contours (Figs. 8a, 8b) show that yawing the upstream turbine throws its wake slightly in the opposite direction ($-y$). As also observed in the vorticity contours (Fig. 9), and the Q-criterion iso-surfaces (Fig. 10), the spiraling vortical structures emanating from the blade tips and roots not only incline in the $-y$ direction but towards the ground. The interference of the tip vortices with the ground and the resulting vortical structures produced ahead of the downstream turbine are clearly visible. The angular deviation of the wake center from the main wind direction is about $5^\circ$ on the horizontal plane and about $1^\circ$ on the vertical plane. Such an inclination of the wake is observed to clear the downstream turbine from operating fully in the wake of the upstream turbine.

Fig. 11 shows the wake deficits behind the rotors for both the wind-aligned and the yawed upstream turbine. As expected, in the wind-aligned rotor case the velocity deficit profiles remain almost symmetrical about the rotation axis on the horizontal plane, while their symmetry is slightly distorted in the vertical plane due to the ground effect. However, in the yawed case, it is clearly observed that the wake deficit behind WT1 shifts in the $-y$ direction. As a result, the downstream turbine does not see a wake deficit in almost half of its vertical plane.

3.3. Power production of turbines in tandem

The power production histograms of both turbines under both the wind-aligned and the yawed upstream turbine cases are presented in Fig. 12. As observed, the upstream turbine converges to a constant power production following an initial transition, and the yawed turbine produces about 14.6% less power than the wind-aligned turbine. As expected, the power production of the downstream turbines start off as the wind aligned turbine. As they start operating under the wake deficit of the upstream turbine at about $t = 120s$, their average power productions drop and start undergoing high frequency variations in time, which is attributed to the unsteady interactions between the blades and the incoming turbulent structures. The average terminal power production coefficients of the turbines are given in Table 1.

In the wind-aligned upstream turbine case, at about $t = 400s$, the power coefficient of WT2 drops to its terminal value of 0.017, which is about 86% less than the upstream turbine. Such a high power deficit for the WT2 is attributed to the absence of atmospheric turbulence and fully
turbulence-free inflow assumption, which leads to a slow wake recovery. Nevertheless, it is in a good agreement with the findings of Schmitz and Jha [22] who employ a similar methodology for the same configuration. Similarly, Miao et al. [23] predicts 80% power loss in their blade resolved URANS simulations with the SST $k-\omega$ turbulence model on a multi-reference frame computational grid with about a total of 20M cells.

In the yawed upstream rotor case, the power production of the upstream turbine is about 15% less than that of the wind aligned case, which is due to the reduced normal velocity component in the vertical rotor plane. Burton [24] [10] suggests that the power production of yawed and wind-aligned turbines are related with $C_{P,\psi}/C_{P,0} \approx \cos^2(\psi)$, which corresponds to 17.8% for $\psi = 25^\circ$. In another numerical study, Schramm et al. [25] report a power drop of 14.5% (from
Figure 8: Wake development behind a yawed upstream turbine (mid rotor z-plane cut)

Figure 9: Vorticity contours on x-planes along stream direction (yawed rotor case)

Figure 10: Q-criterion iso surfaces in the yawed rotor case

Table 1: Power output of wind turbines and relative power deficit of WT2 ($\Delta_{CP} = C_{P,WT1} - C_{P,WT2}$).

| $\psi_{WT}$ | $C_{P,WT1}$ | $C_{P,WT2}$ | $\Delta_{CP}$ | $C_{P, Avg}$ |
|------------|-------------|-------------|----------------|-------------|
| $0^\circ$  | 0.492       | 0.071       | 86%            | 0.282       |
| $25^\circ$ | 0.420       | 0.285       | 32%            | 0.353       |

5.6MW down to 4.8MW) for the upstream NREL 5MW rotor when it is yawed by $\psi = 25^\circ$. It agrees well with the current prediction.
On the other hand, the power histogram of the downstream turbine, WT2, reveals the benefit of the deflected wake. The relative power production deficit of WT2 with respect to the upstream turbine drops to a much smaller value of 32% (Table 1) due to the wake deflection of the upstream turbine mentioned above. In their blade resolved full CFD simulations, Miao et al. [23] report a 30.5% relative power deficit at the downstream turbine when the upstream rotor is yawed by 30°. Such a close agreement with a blade resolved unsteady simulation further validates the current implementation of ALM and builds confidence in its capability of yielding accurate predictions.

To gain a better insight into how the downstream turbine (WT2) is affected by yawing of the upstream turbine, the contributions of a single blade to the turbine’s power production during each revolution are compared in Fig. 13. Data is plotted cyclically for the last 5 revolutions of the rotor. In addition to the two ABL inflow cases, the contribution in the case of a uniform inflow is also considered for validation. As expected, under the uniform inflow, the power productions of the WT1 and WT2 blades are almost constant and the WT2 blade contributes about 1/6 of the WT1 blade in agreement with Table 1.

In the cases of the ABL inflow, the power histogram of the wind aligned blades are symmetric about vertical axes as expected. Since the wind velocities are set to 8m/s at the hub height in both the uniform and the ABL inflow cases, a single blade under the ABL inflow produces more power when it is away from the ground position (180°), and it is more significant for the WT1 blade. In the case of yawed upstream blade, its symmetric power production is lost. More importantly, the increase in the power production of the downstream blade is clearly observed. Since the WT2 blade produces more power when its interference with the inclined wake of the upstream turbine is minimum, it is again concluded that the wake behind the yawed upstream blade is deflected downward and in the −y direction.

4. Conclusion
The wind fields over two turbines in a tandem configuration are successfully simulated based on the actuator line model coupled with the OpenFOAM’s incompressible LES solver pimpleFoam. It is shown that once the simulation parameters are fine-tuned, the coupled solver developed is capable of generating the tip vortices and unsteady wake deficits behind wind aligned and
yawed upstream rotors, and predict the power generation of the individual turbines in tandem configurations. It is also shown that the present power production predictions are also in good agreement with the similar studies and with those of the blade resolved URANS solutions. The LES based turbulent flow solutions coupled with the actuator line model yield accurate predictions with a relatively low computational cost compared to the blade-resolved simulations. It is concluded that the current ALM based wind field solver is capable of simulating a wind farm for a short term power forecasting.

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**Figure 12:** Power coefficient ($C_P$) histogram of upstream and downstream wind turbines

**Figure 13:** $C_P$ contribution of a single blade, periodically plotted over the last 5 revolutions

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