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An actuator line simulation of wind turbine wake with linear upwind stabilized transport scheme#

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ABSTRACT

The wake interactions between wind turbines in large wind farms significantly impact optimal layout and power generation. Therefore, it is crucial to accurate prediction of turbine wake development. In this study, we utilize Large Eddy Simulation (LES) coupled with the actuator line method to investigate the flow of wakes downstream of a scaled wind turbine model and the NREL 5MW turbine. To improve the accuracy of wake simulations, we propose a novel difference scheme called the linear upwind stabilized transport (LUST) scheme, which we compare to the second-order central and upwind schemes. Our results demonstrate that the LUST scheme provides proper numerical dissipation for wind turbine wake simulations, leading to improve accuracy in predicting mean velocity and turbulent intensity when compared to experimental measurements. Furthermore, the LES results indicate that the dissipation introduced by the LUST scheme stabilizes numerical simulations while still capturing small scales in the flow field. These findings highlight the effectiveness of the LUST scheme in accurately simulating wind turbine wakes and emphasize the importance of proper numerical dissipation in obtaining reliable results.

Keywords: Wind turbine wakes, Large Eddy Simulation, actuator line method, linear upwind stabilized transport scheme

1. INTRODUCTION

During the operation of wind turbines, they generate wake effects that have several negative consequences. These effects include a decrease in wind speed and an increase in turbulence downstream. As a result, the downstream turbines experience reduced incoming wind speed, leading to lower power generation, increased loads on the turbines, and a shorter lifespan [1]. In large-scale wind farms consisting of numerous turbines, the impact of wake effects becomes even more substantial. It can significantly influence the optimal layout of turbines and the forecasts of power generation [2]. Therefore, it is crucial to accurately predict the evolution of wake effects to mitigate their adverse effects on wind farm performance.

The most accurate wind turbine modeling method is to generate a mesh for the full rotor, which captures fine flow structures near the blades. However, this method is rarely used due to difficulties in handling wind turbine rotation and requiring significant computing resources [3]. To overcome these challenges, researchers have proposed actuator methods, including the actuator disc, actuator line, and actuator surface methods. Among these, the actuator line method processes each blade separately to obtain vortex structures in wake flows [4], making it an appropriate choice for modeling wind turbines in this study.

Numerical simulation methods for flow fields in wind turbine wakes include the Vortex Lattice Method (VLM), Reynolds Averaged Navier-Stokes Method (RANS), Detached Eddy Simulation method (DES), and Large Eddy Simulation method (LES). The VLM method is fast and easy to implement, but cannot predict flow near blade roots due to detached vortices downstream of the blades. RANS models are based on the homogeneous Boussinesq hypothesis, but wind turbines operate in highly anisotropic atmospheric boundary layers that render standard RANS turbulence models inadequate for accurately capturing unsteady three-dimensional flow structures, necessitating revisions [5]. DES is a hybrid numerical solution combining RANS and LES methods, solving boundary layer flows using RANS and far field flows with LES, providing better prediction of complex wake flows in multiple wind turbines. However, a gray zone at the junction of the two simulation domains leads to inaccurate viscosity and large errors in LES solutions [6].

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In the LES studies of wind turbine wake development, the most commonly used methods include both spectral difference method and finite volume method. Wu et al. [7] and Martinez et al. [8] used a high-precision spectral difference method to simulate the wake flow of a model wind turbine and measured the wind flows in a wind tunnel, with the predicted average velocity distribution showing good agreement with experimental measurements. The EllipSys3D program developed by the Technical University of Denmark adopts a structured grid-based finite volume method, with the convection term discretized using a third-order upwind/fourth-order center hybrid scheme [9]. This program has been used by numerous researchers to investigate the wake flows of wind turbines and wind farms. OpenFOAM is an open source Computational Fluid Dynamics (CFD) software package that discretizes Navier-Stokes equations on unstructured grids. NREL has developed a wind turbine wake simulation library called SOWFA based on OpenFOAM, which can discretize convection terms in many different ways, including first-order upwind/second-order center hybrid schemes and other stable schemes using different limiters [10-12].

In conclusion, numerical discrete schemes play a crucial role in accurately simulating flow physics. The spectral difference method has high accuracy and low dissipation when combined with subgrid scale models specified for atmospheric boundary layer simulations, making them suitable for simulating wind turbine wakes under flat terrain conditions. However, their use of Fourier expansions requires periodic boundaries, making it difficult to deal with complex boundary conditions. Structured grid-based finite volume solvers like EllipSys3D face challenges generating high-order schemes, and using low-order schemes can introduce significant numerical dissipation masking the subgrid scale model. Unstructured finite volume solvers like OpenFOAM can handle geometric boundaries better, but still struggle with constructing high-order schemes. Therefore, constructing a numerical discrete scheme with high precision and good stability is very important for wind turbine wake simulation. It is vital to choose a method that can handle the computational domain's geometrical complexity and generate accurate results while maintaining computational efficiency.

Based on the discussion above, this paper uses Large Eddy Simulation (LES) to discretize the Navier-Stokes equations and models the wind turbine using the actuator line method. Additionally, the conception of the actuator line method is introduced to model the nacelle and tower of the wind turbine. The wake flows of a scaled model wind turbine and the NREL 5MW wind turbine are simulated in the neutral atmospheric boundary layer. The study proposes a numerical discrete scheme with higher accuracy and good stability while also examining the influence of different convection discretization schemes on LES simulations of wind turbine wakes.

2. NUMERICAL METHODS

2.1 Governing equations

The numerical simulation in this paper uses the open-source software OpenFOAM, combined with the wind turbine wake simulation library SOWFA [6], developed by NREL. The simulation method adopts the finite volume method to solve the incompressible Navier-Stokes equations on an unstructured grid.

$$\nabla\cdot\tilde{u} = 0 \qquad (1)$$

$$\frac{\partial\tilde{u}}{\partial t} + (\tilde{u}\cdot\nabla)\tilde{u} = -\frac{1}{\rho}\nabla\tilde{p} + \nu\nabla^2\tilde{u} - \nabla\cdot\tau_{SGS} + \vec{f}_{turbine} \quad (2)$$

where u ̃ and p ̃ are the filtered velocity and pressure. The filter size in this paper is taken as the grid size. ν represents the kinematic viscosity, and f┴→ _"turbine" is the source term that characterizes the influence of the wind turbine on the flow field, which will be described in detail later in the paper. τ_"SGS" is the sub-grid stress, which is calculated using the classic Smagorinsky sub-grid scale model. Buoyancy effects caused by temperature differences are ignored since the wind turbine is located in the neutral atmospheric boundary layer, and hence, the temperature equation is not solved.

2.2 Discretization methods

In Large Eddy Simulation (LES), the discrete method for the convection term in the Navier-Stokes equation is critical since it is non-linear. Using a pure central scheme with small numerical dissipation can introduce non-physical oscillations and distort the flow fields. The upwind scheme, on the other hand, is too dissipative and can smooth out small-scale structures in the flow fields. When the solution is stable, the second-order central difference scheme (referred to as the linear scheme) is considered the best choice for LES in a finite volume framework [9]. Considering the stability of the central difference scheme, the second-order upwind scheme (hereinafter referred to as the linearUpwind scheme) can effectively stabilize the numerical solution process. However, it is generally accepted that the dissipation of the second-order upwind difference scheme is too large for Large Eddy Simulation of wind turbine wakes, so a new linear upwind stable transport scheme (hereinafter referred to as the LUST scheme) is proposed [13].

$$\varphi_{\mathrm{f,LUST}} = \lambda\varphi_{\mathrm{f,linearUpwind}} + (1-\lambda)\varphi_{\mathrm{f,linear}} \tag{3}$$

The LUST scheme can not only ensure the stability of numerical solution, but also reproduce the fine structures of the flow fields. The mixing coefficient λ represents the proportion of the introduced upwind dissipation. The larger value of λ means greater numerical dissipation, leading to better numerical stability. Smaller λ means that the hybrid scheme is closer to the linear scheme. Hilary Weller [14] compares different values of λ and recommends λ=0.25. After a series of numerical tests, it is found that λ="0.25" can better balance the stability and computational consumption of the wind turbine wake simulation process and is used in the following simulations.

2.3 Wind turbine modelling

This paper uses the actuator line method to model the wind turbine, which simplifies each blade into a source term of volume force, and uses a three-dimensional Gaussian function to apply the volume force to the numerical cells.

The traditional actuator line method ignores the influence of the nacelle and the tower, resulting in a large deviation in the prediction of the near wake. This paper adopts a new modeling method based on the potential flow theory. This is an idea similar to the actuator line method to include the influence of the nacelle and tower on the flow field.

The numerical simulation in this paper refers to the wind tunnel experiment conducted by Chamorro et al. [9]. The simulation domain is set as Lx=4.32m, Ly=0.72m, and Lz=0.46m, where Lx, Ly and Lz are length scales in the flow, span and normal directions. The wind turbine lies at the spanwise center of the wind tunnel, and 6D from the inlet, where D=0.15m is the wind turbine diameter. The computation grid contains 270×46×30 in the three directions, giving a uniform grid size of 0.016m.

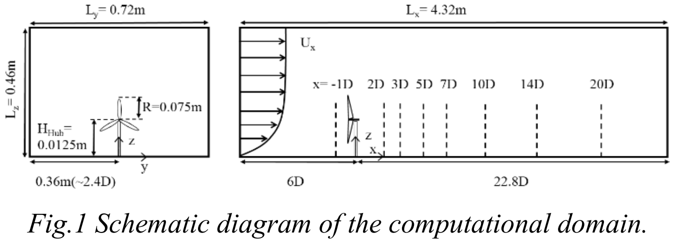


Fig.1 Schematic diagram of the computational domain.

3. RESULTS AND DISCUSSIONS

3.1 Inflow conditions

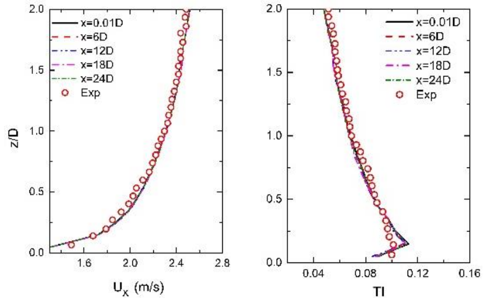
Before simulating the wake flows of a wind turbine, it is necessary to verify the uniformity of the precursor flow field to ensure that the velocity and turbulence intensity distribution are consistent in the flow direction of the calculation domain, that is, the calculation method can maintain uniformity of the flow field in the entire calculation domain. Figure 2 shows the average flow velocity and turbulence intensity profiles at different flow directions when simulating the atmospheric boundary layer without wind turbines. The red circle shows the results of the EPFL wind tunnel experiment, and the others are the numerical results reported by LES, which are sampled at different positions along flow direction. x=0.01D is sliced for the inlet position.

From the comparison between the LES results and the wind tunnel experiment results, it can be seen that the average velocity and turbulence intensity of the numerical simulations are in good agreement with the experiment, especially in the area far away from the lower wall of the wind tunnel. Near the lower wall, the wind tunnel experiment uses a coarse wire mesh to stimulate the scaled atmospheric boundary layer, and the numerical simulation uses the so-called wall function instead. Therefore, there are some differences for the simulation results of the turbulence intensity. Since there is a certain distance between the wake region and the lower wall of the wind tunnel, the influence of the error on the wake prediction can be ignored. The logarithmic fitting of the velocity measured in the wind tunnel experiment shows that the equivalent wall friction velocity is 0.102 m/s, and the fitting result of the numerical calculation is 0.095 m/s, with an error of 6.8%.

3.2 Validations of LUST scheme

Figure 2 shows the normal distribution of the velocity turbulence intensity along the normal direction at 8 different positions before and after the wind turbine calculated using the LUST format. The specific position of the profile is marked in Figure 1. The wind turbine is located at x=0, hub height is at z/D=0.83. x/D=-1 is located at 1D upstream of the wind turbine, whose result represents the incoming wind speed. x=2D and x=3D corresponds to the near wake region of the wind turbine. And after x=5D correspond to the far wake region.

It can be seen from Figure 3 that the large eddy numerical simulation using coarse grids can better predict the upstream and downstream velocity distribution of the wind turbine. The numerical simulation of the incoming wind speed is completely consistent with the experimental measurement results, and the average velocity distribution in the far wake region is also consistent with the experimental results basically. The maximum error between the numerically calculated speed and the experimental results below the near-wake hub is about 8%, indicating that the existing nacelle and tower models cannot fully characterize the influence of these two entities on the flow field.



(a) (b)

Fig. 2 Profiles of mean velocity (a) and turbulence intensity (b) distribution at different flow directions.

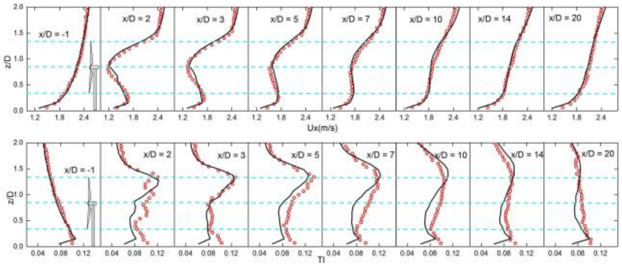


Fig.3 Velocity and turbulence intensity distribution at different positions before and after the wind turbine along the flow direction (Upper: velocity, Lower: turbulence intensity. Red dots are experimental values, black lines are calculated values).

From the comparison of turbulence intensity, it can be seen that above the height of the hub, the turbulence intensity obtained by large eddy simulation is closer to the experimental measurement result. In the near wake region (x=2D and x=3D), the turbulence intensity at the height of the nacelle is basically consistent with the experiment, indicating that the calculation method used in this paper can better simulate the effect of the nacelle on the flow field. Below the hub height, the turbulence intensity calculated by the large eddy simulation is quite different from the experiment. From the near wake region to the far wake region (x=2D to x=20D), this error first increases and then decreases. It shows that although the tower model can reflect the influence of the tower on the wake prediction, there is still a certain error. After the wake develops for a certain distance downstream, the predicted turbulent intensity is significantly smaller than the experimental value, which is mainly caused by the rough grid.

3.3 Comparisons of different convective discretization schemes

In order to further illustrate that the LUST format can effectively predict wind turbine wakes, we used three discrete formats to perform numerical simulation, and extracted eight velocity profiles at different locations for comparative analysis (Figure 4). In general, the three different discrete methods can basically predict the average result of wake velocity better. The main error occurs in the near wake region upstream of x=7D. The mean velocity distributions predicted by the central difference scheme (linear) and the LUST scheme are basically indistinguishable. The near-wake velocity calculated by the second-order upwind formula (linearUpwind) is too big, that is, the velocity deficit is smaller than the experimental measurement value. This is mainly due to the large dissipation of the pure windward type format, which will smooth out the small-scale structures in the flow field, and the main energy is concentrated in the large-scale motion, so the predicted average flow velocity is large. In the far wake region, the predicted results of the mean velocity profile are less affected by the discrete format.

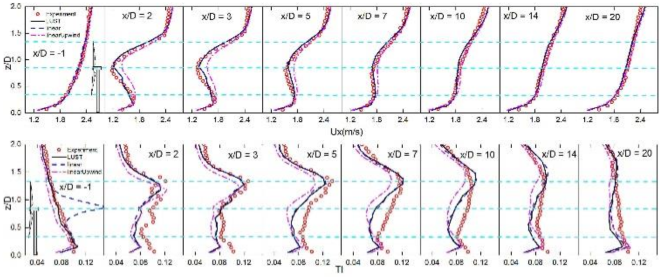


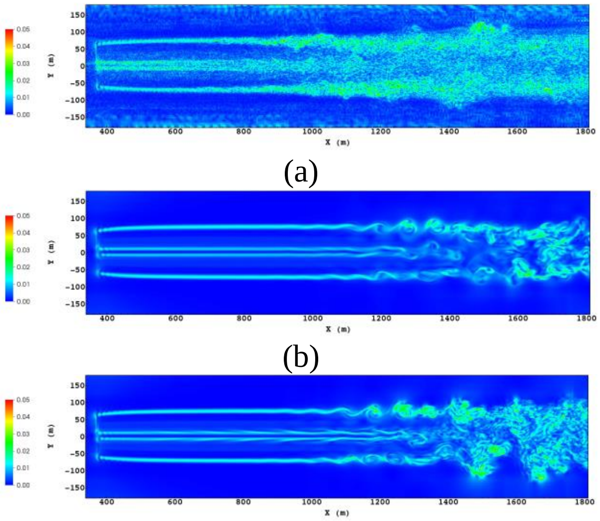
Fig.4 Distribution of mean flow velocity and turbulence intensity in wind turbine wake predicted by different discrete formats.

It can be seen from Figure 4 that compared with the velocity, the prediction error of the turbulence intensity in the wake region is larger. Note that in the upstream region of the wind turbine at x=-1D, the turbulence intensity predicted by the central difference scheme is significantly larger at the hub height. This is mainly due to the fact that the presence of the wind turbine causes the fluid upstream of it to slow down and increase the pressure. Therefore, there will be a checkboard pressure field in this area, and the central difference scheme cannot eliminate the sawtooth wave in the pressure distribution, which will cause false oscillations in the velocity, and make the average turbulent intensity high. It can be seen from the above analysis that the discrete convection term of the pure center type format should be avoided as far as possible in the simulation of wind turbine wake, and the LUST format shows good stability.

After the region of x/D=2, the turbulent intensities calculated by the three methods are all smaller than the experimental values. In contrast, the linearUpwind method causes the largest error, especially in the near wake region. The turbulent intensities calculated by the linear format and the LUST format are basically the same, which are closer to the experimental values, again indicating that the dissipation level of the linearupwind format is too high, reducing the real velocity pulsation.

3.4 Flow simulation downwind a NREL 5MW wind turbine

To demonstrate the differences between various schemes, flow parameters in the wake are presented. Figure 5 and 6 show the contours of instantaneous SGS viscosity and vorticity after the rotor. For the case of linear discretization (a) of the viscosity depiction, it is obvious the SGS viscosity predicted by LES is distorted since it has too much small structures depicted in the Q contour, especially in the vicinity of refined mesh. This is understandable because the mesh design is intended to satisfy the condition that blade tip should not pass more than one grid in each time step and the mesh amount should be acceptable, however this does not meet the stability requirement for linear scheme that Peclet number should not exceed 2. The high viscosity passage is sustained to the extent of 8D and 10D downstream the rotor for LUST scheme and linearUpwind scheme indicating that LUST introduces less numerical diffusion than linearUpwind. However, the Q contours indicate that LUST, and linearUpwind give legible vortex structure downstream the rotor owe to the numerical dissipation introduced in these schemes. It is also noted that the percentage of linearUpwind in LUST scheme is 25% which seems too diffusive.

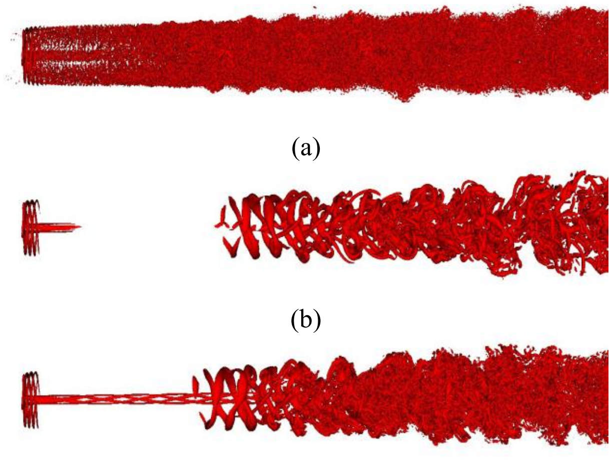


(a)

(b)

(c)

Figure 5. Instantaneous snapshot of SGS viscosity predicted by different convective schemes, (a) linear; (b) linearUpwind; (c) LUST.



(a)

(b)

(c)

Figure 6. Instantaneous snapshot of Q criteria after the wind turbine, (a) linear; (b) linearUpwind; (c) LUST.

4. CONCLUSIONS

Using the large eddy simulation numerical method based on actuating lines, the wake development process of wind turbines under the condition of neutral atmospheric boundary layer is studied in this paper. Comparing the numerical simulation results with the experimental measurement results of the wind tunnel, it is found that the predicted mean flow direction velocity distribution is in good agreement with the experimental results, while the turbulence intensity is smaller than the experimental value. This is mainly because the large eddy simulation method filters the flow field and filters out turbulent pulsations smaller than the grid scale.

The convection terms are discretized in three different formats when solving the Navier-Stokes equations. The influence of discrete scheme on the prediction results of wind turbine wake average velocity and turbulence intensity distribution is analyzed. By comparison, it can be found that in the process of wind turbine wake simulation, the use of the second-order central difference scheme will lead to odd-even disconnection of pressure, and a checkerboard-shaped velocity field will be generated upstream of the wind turbine, resulting in false numerical oscillations. The use of the second-order upwind style can better suppress numerical oscillations, but it will smooth out the small-scale structure of the flow field, resulting in a small velocity deficit and turbulent intensity. The LUST method can not only ensure the stability of the numerical solution process, but also simulate the small-scale pulsation structure in the flow field, indicating that the LUST method can provide reasonable numerical dissipation in the large eddy simulation of wind turbine wakes.

It is worth noting that although the LUST format is relatively stable, it contains an adjustable empirical parameter that needs to be adjusted according to specific examples. We therefore suggest that the next step should be to develop a stable discrete format without empirical parameters for large eddy simulation of wind turbine wakes.

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