Applied Energy 144 (2015) 224–233

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Lagrangian dynamic large-eddy simulation of wind turbine near wakes combined with an actuator line method

Hongmin Zhong [a,b,*], Pingan Du [a], Fangning Tang [c], Li Wang [a]

[a] School of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
[b] School of Mechanical Engineering, Sichuan University of Science and Engineering, Zigong 643000, China
[c] Wind Power Business Unit, CSR Zhuzhou Institute Co., Ltd., Zhuzhou 412001, China

HIGHLIGHTS

- A Lagrangian dynamic LES model combined with ALM is proposed.
- Several justified model parameters from the literature and experiment are utilized.
- The model is compared to the MEXICO measurements.
- Near wake characteristics are studied at three different tip speed ratios.

ARTICLE INFO

Article history:
Received 27 July 2014
Received in revised form 20 January 2015
Accepted 21 January 2015
Available online 27 February 2015

Keywords:
Lagrangian dynamic LES
Actuator line method
Wind energy
Near wakes
Velocity deficit
MEXICO

ABSTRACT

Wind turbine wakes have significant effects on the production efficiency and fatigue loads, and these effects should be considered in the optimization of wind turbine structure and wind farm layouts. In this paper, a numerical model combining Lagrangian dynamic large-eddy models and actuator line methods (ALMs) is implemented to investigate the wind turbine near wakes at three representative tip speed ratios (TSRs). In the model, several model parameters that have been justified based on the existing literature and experiments are utilized to enhance the numerical stability and accuracy. These parameters are related to a physically meaningful length scale in the Gaussian smoothing function, a Prandtl tip/hub-loss factor and a 3D correction for airfoil data. The model is compared to the MEXICO measurements, in which a detailed stereo PIV measurement is carried out. According to the comparison of rotor power coefficients between the prediction and the measurements, there is a slight overestimate at TSRs of 6.67 and 10, while a slight underestimate at TSR of 4.17. Additionally, according to the comparison of streamwise traverses and spanwise distribution of axial velocities, good agreement is achieved at both TSRs of 4.17 and 6.67, while visible difference is found at TSR of 10. Moreover, the simulation result shows a helical behavior of wake tip vortices induced by the turbine rotor. This behavior gets more pronounced with a decreasing TSR. The tip vortices also give a reasonable explanation of why the maximum velocity deficit and turbulence intensity occur near the blade tip of wind turbines.

1. Introduction

An emerging awareness of the sustainability and cleanliness of renewable energy have inspired many governments (or organizations) to formulate (or reformulate) a new energy policy to stimulate economies, diversify energy supply and reduce dependence on fossil fuels. In the new policies scenario, the installed capacity worldwide of wind energy (both onshore and offshore wind), as one of renewables, will increase from 1465 GW in the end of 2011 to 3770 GW in 2035, according to the projection from IEA (the International Energy Agency) [1, Chapter 7,2, Chapter 6,3,4]. However, it is generally believed that the meeting of the targets may be confronted with a wide range of challenges such as technologies, investments and management. Nowadays the wind turbines clustered highly in wind farms are widely used to reduce space and operation and maintenance (O&M) costs. Therefore, the optimum way of wind turbine clusters should be concerned, which is related to many factors such as wind velocity, terrains, instability effects of atmospheric boundary layer and unsteady wakes among wind turbines.

---

* Corresponding author at: School of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China. Tel.: +86 13568320296; fax: +86 813 5505867.

E-mail address: zhmhongmin@hotmail.com (H. Zhong).

http://dx.doi.org/10.1016/j.apenergy.2015.01.082
0306-2619/

Unsteady turbine wakes exhibit two important characteristics, velocity deficit and turbulence intensity, which are related to power losses and dynamic load, respectively. Thus a good understanding of wind turbine wakes is indispensable to minimize the potential investment risks. A great quantity of studies on wind turbine wakes in wind farms have been emerging due to their closely relating to wind energy extraction efficiency, dynamic load (linked to rotor fatigue life and stability of electricity grid systems), and even environmental impacts (such as killing birds and aerodynamic noise) [5–9]. According to the blade element momentum (BEM) model and lifting line free vortex wake method [10], which have been widely applied so far in the wind energy industry, wind power efficiency involves average velocity deficit in wakes, i.e.,

$$C_p = 4a(1-a)^2, \tag{1}$$

where C_p is the power efficiency, and a is the axial induction factor, whereas the dynamic load is related to the turbulent intensity in wakes [11], and under reasonably simplified conditions, we can obtain

$$\overline{F} = \frac{1}{2}\rho\langle C_f\rangle AU^2(1+I_u^2), \tag{2}$$

here $\overline{F}$ is the total force applied on the turbine, I_u is the turbulent intensity in wakes, the angle bracket $\langle\rangle$ refers to a spatial average over the rotor area, $\rho,\ C_f,\ A$ and $U$are the air density, the aerodynamic lift coefficient, the rotor area and the mean wind velocity, respectively. In general, the turbulent intensity of the wake I_u in (2) can be estimated by an empirical formula [12,13] or a numerical simulation method [6] for the optimization design of wind farms. Thus the optimization of both rotor blade design and wind farm layouts to some extent hinges on the insights into wind turbine wake aerodynamics. Although the BEM and empirical formulas play an important role in the field of wind turbine aerodynamics, their estimate accuracy is still in doubt for complex terrain and wind conditions. This just sparks an interest in a wide variety of numerical simulation methods.

We focus on an efficient and accurate numerical model for the aerodynamics of wind turbine wakes. The model is compared to the experimental data from the European Union (EU) project called MEXICO [14]. Generally speaking, the practical turbine wake is a turbulent flow with high Reynolds number which is governed by the Navier–Stokes equations (NSE) with a large range of length and time scales. Based on the philosophy of the Kolmogorov turbulent energy cascade, three well-known numerical methods for solving NSE, direct numerical simulations (DNS), Reynolds-averaged Navier–Stokes (RANS) and large-eddy simulation (LES), have been applied [15]. DNS resolves the full-scales turbulence eddies from the integral length scale, which characterizes the energy-containing motions, to the Kolmogorov scale, which characterizes the smallest eddy motions, while RANS models the full-scales turbulence eddies and LES partly resolves/models them. From the perspective of resolving capability, the simulation accuracy increases from RANS to LES to DNS [15,46]. However, DNS is beyond our current capability owing to a prodigious computational expenditure for complex engineering problems. Furthermore, large numbers of experiments have shown that there exists a complicated vortex system in turbine wakes covering tip vortices, root vortices, meandering and their interaction [6,16]. Thus, LES should be more suitable than the other two methods to simulate the complicated wake vortex system when considering a tradeoff between computational accuracy and costs. In LES, the large eddy motions whose scale is larger than the resolved scale (also called filter or grid scale) are resolved directly while the subgrid-scale (SGS) stress which represents the physics of the unresolved scales is modeled by a SGS model. A large number of SGS models have been implemented [17], of which the Lagrangian dynamic SGS model based on the Smagorinsky model [18] is the interest of the paper. In the model, the Smagorinsky coefficient is determined dynamically in accordance with the resolved field information by minimizing the Germano-identity error over the fluid particle trajectory rather than over the statistical homogeneity directions.

However, if full rotors are computed by LES, the total number of grid points required is proportional to $Re^{2.4}$ to resolve the boundary layer [19]. Thus, it is hardly suitable for the simulation of turbine wake due to the excessive requirements of computing resources. To circumvent the problem, two prevalent avenues, the simplifications either for the flow governing equations (i.e., the Navier–Stokes equations) or for the flow over the turbine rotor, can be found in Refs. [5,6,16]. To be specific, for the former a parabolic or elliptic model was put forward by Crespo et al., while for the latter the actuator disc/line/surface methods were successively brought forth, in which the body forces exerted on the flow by the turbine blades as source terms are introduced into the momentum equation [20,21,23]. The great benefit of the actuator methods is that rotational effects of rotor blades are modeled instead of resolving the airfoil viscous boundary layer, and hence the total number of grid nodes is reduced significantly compared to the full rotor computational fluid dynamics (CFD).

Although many researchers have devoted a great deal of effort in the numerical study of wind turbine wake aerodynamics in recent years [24–27], different numerical models are still necessary due to different potential goals. In the present work, a LES numerical model for the simulation of wind turbine wakes, combining the Lagrangian dynamic SGS model with ALM, is proposed, taking into account several additional model parameters from the literature [10,28–30]. These model parameters involve the length-scale choice of the Gaussian smoothing function (or the regularization kernel) [28], the Prandtl tip/hub-loss factor [29,10] and the 3D correction for airfoil data [30]. It deserves to be mentioned that the proposed numerical model is based on incompressible conditions due to low Math number (< 0.3), and is compared to the MEXICO measurements [14,31]. In comparison with the well-known project NREL NASA Ames wind tunnel experiment, the most outstanding feature of MEXICO is that a detailed stereo particle image velocimetry (PIV) measurement of the upstream and downstream of the wind turbine was carried out, besides pressure and load measurements. The measurements were done on a three-bladed horizontal axis wind turbine (HAWT) with a diameter of 4.5 m, which was placed in the Large Low Speed Facility (LLF) of the German Dutch Wind Tunnel (DNW) with a size of 9.5×9.5 m. The blade Reynolds number of the MEXICO rotor has the same order as that of most nowadays commercial wind turbines roughly between 3.2×10^5 and 1.6×10^6. The measurement data for the present LES numerical model validation is from three representative cases, i.e. three free stream wind speeds U_0 of 10, 15 and 24 m/s, which represent turbulent wake state, design conditions and stalled conditions, respectively [10]. In addition, although the present work is accomplished using the DNW wind tunnel model, it may well be applicable to the wake simulation of wind farms with some minor changes. For example, an atmospheric boundary layer (ABL) is taken into consideration.

For the wind farms installing many wind turbines, wake effects have a significant impact on power generation efficiency, rotor fatigue life and stability of electricity grid systems, which remain the prime concern for investors. However, the wind power engineering community generally has to use low-accuracy empirical model to deal with these effects due to the complexity of wakes. In the future, more large-scale wind turbines will be erected in big onshore or offshore wind farms, and this means that a detailed knowledge of the aerodynamic and aero-elastic loading of turbines,