Large Eddy Simulation of Wind Turbine Wake by using Actuator Line Model
Part 2: Coriolis force effects and its validation by field measurement

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1. Introduction

Wake steering control is a promising strategy to tackle wake loss during the operation of the wind farm, where the wake is deflected away from its downstream turbines by imposing an intentional yaw offset. Studies on wake characteristics in real scale revealed that the Coriolis force also deflects a wind turbine wake with respect to the incoming wind[1]. Hence, the Coriolis force effect should be carefully considered when applying wake steering control in real wind farm.

However, the previous numerical studies on Coriolis force lack of validation[1]. In addition, recently, the field campaign shown that the conventional wake model could not reproduce characteristics both of near and far wake regions in real scale.[2] In part 2, the developed LES simulation framework incorporating the Coriolis force is applied to a utility wind turbine and validated by the field measurement data.

2. Numerical model

2.1 Actuator Line Model

The effect of the rotor induced forces on the flow field is parameterized by using the Actuator Line Model[3]. In this model, the turbine blades are represented by three rotating lines which are discretized into several blade elements, where the lift and drag forces are calculated based on the blade element theory. Figure 1(a) shows the schematic of the ALM model, where x is streamwise direction aligned with the incoming wind speed U_n.

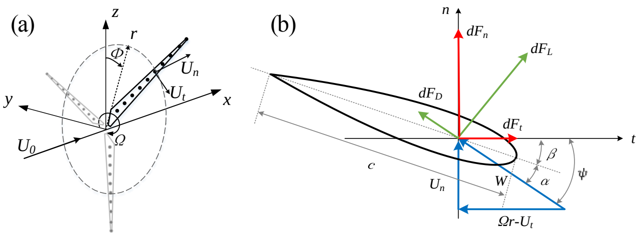

Figure 1 Schematic of the ALM model: (a) axis system for a rotor and rotating element, (b) velocities and forces acting on a cross-sectional blade element.

The relation between wind velocity and forces acting on a blade element of length dr located at the radius r is shown in Figure 1(b), where n and t denote the axial and tangential directions respectively, α is the angle of attack, β is the local pitch angle and ψ is the angle between the relative velocity and the rotor plane. dF_L and dF_D are the lift and drag forces acting on the blade element and given by:

$$dF_L = \frac{1}{2}\rho W^2 c C_L dr,\ dF_D = \frac{1}{2}\rho W^2 c C_D dr \tag{1}$$

where c is the chord length. C_L and C_D are the lift and drag coefficients, respectively. W is the local relative velocity with respect to the blade element. A 3D gaussian distribution function is applied to project the aerodynamic force smoothly from each blade element to grid points in the CFD simulation by the following equation:

$$f_{rot,i} = \begin{bmatrix} f_n \\ f_t \end{bmatrix} = \begin{bmatrix} dF_L\cos\psi + dF_D\sin\psi \\ dF_L\sin\psi - dF_D\cos\psi \end{bmatrix} \cdot \eta \tag{2}$$

$$\eta = \frac{1}{\varepsilon^3 \pi^{3/2}} exp\left[-\left(\frac{\tau}{\varepsilon}\right)^2\right] \tag{3}$$

where ε is a smoothing parameter taken equal to 2Δ.

2.2 Coriolis force

To introduce the earth rotation induced deflection effect, Coriolis force is also included into the numerical model by using the following equations.

$$f_{cor,i} = -2\varepsilon_{ijk}\Omega_j\widetilde{u_k} \tag{4}$$

$$\Omega_j = \omega\begin{bmatrix} 0 \\ \cos\varphi \\ \sin\varphi \end{bmatrix} \tag{5}$$

where ε_{ijk} is the alternating unit tensor, ω is the earth rotation rate, and φ is the latitude. Since the vertical component of wind speed and Coriolis force are small, the Coriolis force can be simplified as equation (6).

$$f_{cor,i} = \begin{bmatrix} -\sin\varphi\ \widetilde{u_2} \\ \sin\varphi\ \widetilde{u_1} \\ 0 \end{bmatrix} \tag{6}$$

The rotor aerodynamic force $f_{rot,i}$ and Coriolis force $f_{cor,i}$ is then added as the source term to the momentum in the LES simulation.

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3. Results and discussion

3.1 Test site and field measurement

The measurements were collected from the Choshi offshore wind energy test facility located about 3.5 Km offshore of Choshi city of Chiba prefecture, Japan. As shown in Figure 2, the facility consists of a 2.4 MW wind turbine (MWT92/2.4) with a rotor diameter D = 92 m and a hub height $H = 80$ m, and a meteorological tower located 285 m east from the turbine. A scanning Doppler LiDAR (WindCube100S) is mounted on the platform. The wind condition and turbine operation conditions on 28 September 2016 from 16:00 to 23:00 are selected to conduct the filed validation for current developed numerical framework.

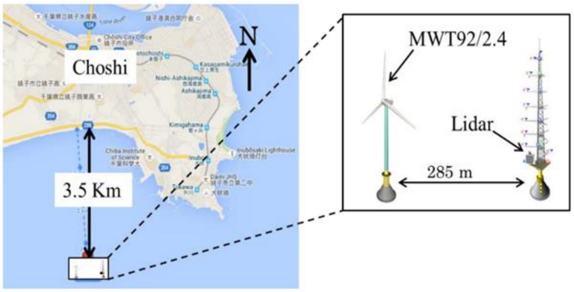

Figure 2 Choshi offshore wind energy test facility

3.2 Wind speed and power

Numerical simulation for the utility-scale turbine is conducted by using the developed LES framework, where the wind speed measured by met-mast is moving averaged with 1-minitue and imputed as the inflow. Figure 3 shows the time series of 1-minitue averaged wind speed and power. It can be seen that the results predicted by LES show good agreement with those measured by met mast and SCADA.

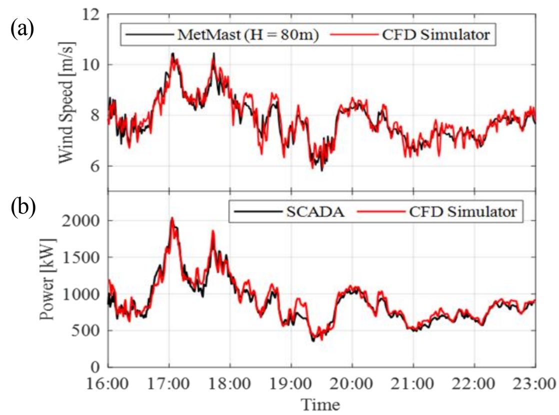

Figure 3 Comparison between simulated results against the measurements. (a) wind speed; (b) power production.

3.3 Wind turbine wake

The mean velocity contour at hub height obtained from LES is shown in Figure 4, where a slight clockwise deflection can be identified in the far wake region. For validation, velocity deficit profiles at selected positions of x =1D and 6D are extracted and compared with those measured by LiDAR in Figure 5, where the results predicted by analytical wake model[4] are also plotted. The developed LES framework can reproduce the dual-peak in near wake region and the Coriolis force induced deflections in far-wake region as well, while the conventional wake model could not capture these two features.

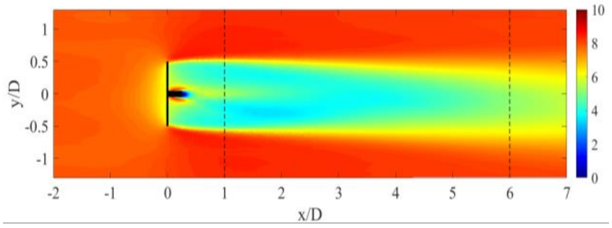

Figure 4 Mean velocity at hub heigh predicted by LES

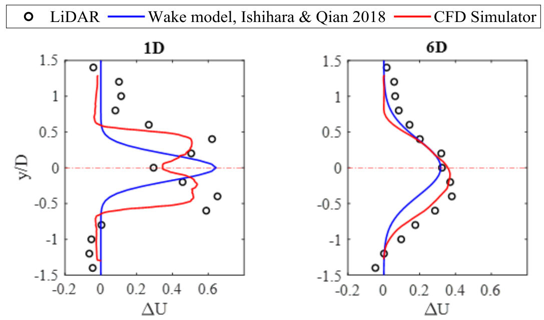

Figure 5 Comparison of velocity deficit profile between measurement, analytical wake model and LES.

4. Conclusion

In this study the following conclusions are obtained:

(1) The developed LES wind turbine simulation framework is applied to a utility site for power prediction and its accuracy is validated by SCADA data.

(2) The wake flow is simulated by considering Coriolis force effects and show favorable agreement with those measured by LiDAR.

Reference

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