Large Eddy Simulation of Wind Turbine Wake by using Actuator Line Model
Part 1: wind turbine control and blade rotation effects

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1. Introduction

The wind farm control by coordinating the greedy control operations across the wind turbines to mitigate the wake induced power losses has been studied around a decade, where wake steering control has been shown to be the best option recently. To evaluate the wind farm control more comprehensively before the engineering implementation, an efficient and accurate approach to simulate the turbine control operations and wake flows is urgently needed.

In previous research, wind farm controls were evaluated using parametric wake models in quasi-steady state, where the control algorithm in the real-time and dynamic wake behaviors in utility operations could not be considered[2]. For numerical wake prediction, the Actuator Disk Model (ADM) has been widely used in wind farm simulation, in which, however, the rotor is modeled by a disk, and the blade geometry and its rotation induced dynamic effects could not be considered in the wake prediction[3].

2. Numerical model

2.1 Governing equation

The finite volume method (FVM) is applied to discretize the governing partial differential equations. In LES, large eddies are directly computed, while the influences of eddies smaller than grid spacing are parameterized, and the incompressible Navier-Stokes equations are filtered as shown follows,

$$\frac{\partial \rho \tilde{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \tilde{u}_i) + \frac{\partial}{\partial x_j}(\rho \tilde{u}_i \tilde{u}_j) = \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)\right) - \frac{\partial \tilde{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + f_{rot,i} + f_{cor,i} \tag{2}$$

where, $\tilde{u}_i$ (i=1, 2 and 3) denote the velocity component in ith direction, $\tilde{p}$ is the pressure, ρ is the air density, and μ is the dynamic viscosity. The momentum source term $f_{rot,i}$ is the rotor aerodynamic force parameterized by Actuator Line Model (ALM), and $f_{cor,i}$ represent the Coriolis force. The detail of them will be introduced in part 2 of this paper.

2.2 Wind turbine controller

The control logic proposed by Yamaguchi[7] is used for the wind turbine controller in this study. In this controller, the generator torque is given as a function of generator speed. In the underrated region, the control target is to achieve the maximum efficiency of the wind turbine. To achieve this, the generator torque Q is controlled as a function of the rotor speed as shown following equations.

$$Q = k_{\mathrm{opt}} \Omega_f{}^2 \tag{3}$$

$$k_{\mathrm{opt}} = \frac{\pi \rho R^5 C_{p_{\mathrm{opt}}}}{2 r^3 \lambda_{\mathrm{opt}}{}^3 \eta_M} \tag{4}$$

In above-rated region, the wind turbine operates at constant power by using the pitch control. The blade pitch angle command θ is given using PI control, as shown in the following equation,

$$\theta_{PI,r}(t) = \kappa \times \left(K_P e(t) + \int_{t_0}^{t} K_I e(t)\, dt\right) \tag{5}$$

where K_p and K_I are the proportional and integral gains determined based on the work by Yoshida[4]. Since the wind flows direction changes over time, a yaw system is required to keep the orientation of a wind turbine aligned with the wind direction to capture as much energy as possible. In addition, the control algorithm proposed by Fleming et al.[5] is adopted for yaw system. The above-mentioned torque, pitch and yaw control are implemented with the LES simulation in current study.

3. Results and discussion

3.1 Verification of wind turbine controller

The benchmark of uniform flow with varying wind direction is designed as shown in Figure 1, where a 6-minitues time series of wind direction consists of 3 steps and the magnitude of wind speed vector keeps constant with U=8 m/s. The designed benchmark wind condition is imposed as the inflow for both LES and FAST.

The step response of turbine operations and aerodynamic forces are depicted in Figure 1. The yaw position can generally track the wind direction while presents a delay to it

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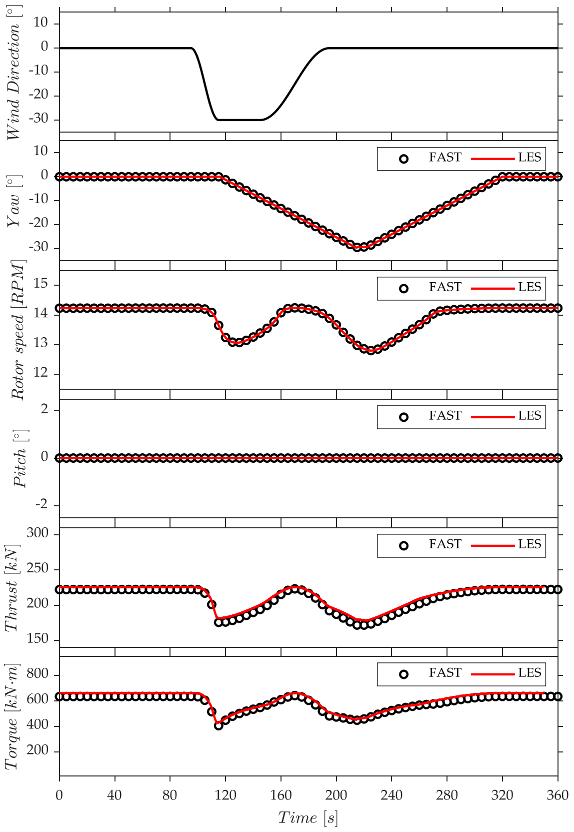

Figure 1 Reuslts of control signals and aerodynamic forces on rotor under varing wind direction

since the rate of wind direction change is much higher than that of yaw motor in real case. The response of thrust force and torque force vary up and down simultaneously following the change of rotor speed. Remark also that the thrust and torque forces simulated by LES show favorable agreement with those calculated by FAST, which implies that the performance of pitch, torque and yaw controller implemented in the current LES framework is verified.

3.2 Blade rotation induced dynamic effects

Figure 2 shows the instantaneous three-dimensional behaviors of the wake flow under turbulent inflow obtained from ADM-R and ALM simulations, in which the vortex structures are visualized in terms of iso-surface plots of the Q criterion colored with normalized streamwise wind speed. The plot of ADM-R simulation clearly presents the ring-like vortex shedding from the edge of rotor disk in the near wake region. While for ALM, since the rotating blades is well modelled, the visualization gives a good impression of the helical structures of the distinct tip vortices within a distance of about 1D downstream the rotor. To further clarify the blade rotation induced dynamic effect, a spectrum analysis for the time series of the thrust force is carried and the result are depicted in Figure 3. For comparison, an aerodynamic simulation with same turbine operate condition is also conducted. In agreement with results calculated by FAST, a clear peak, coinciding with 3P frequency (three times the frequency of rotor rotation), appears in the power spectrum of thrust force calculated by ALM simulation, which however is not captured in the ADM-R.

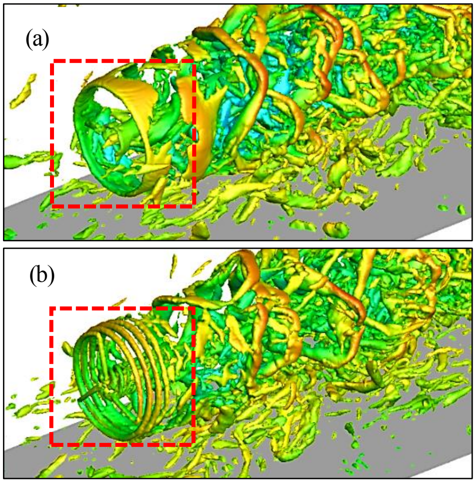

Figure 2 Three-Dimensional vortex structure in the wake flow of wind turbine: (a) ADM-R, (b) ALM.

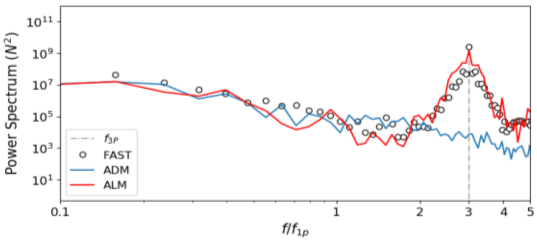

Figure 3 Power Spectrum of thrust force

4. Conclusion

In this study, the following conclusions are obtained.

(1) A LES simulation incorporating wind turbine controller is developed and verified.

(2) A numerical wind turbine model considering the rotor geometry is developed using ALM, where the blades rotation induced aerodynamic effect is reproduced.

Reference

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