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Simulation and optimal control of wind-farm boundary layers

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In large wind farms, the effect of turbine wakes, and their interaction leads to a reduction in farm efficiency, with power generated by turbines in a farm being lower than that of a lone-standing turbine by up to 50%. In very large wind farms or ‘deep arrays’, this efficiency loss is related to interaction of the wind farms with the planetary boundary layer, leading to lower wind speeds at turbine level. Moreover, for these cases it has been demonstrated both in simulations and wind-tunnel experiments that the wind-farm energy extraction is dominated by the vertical turbulent transport of kinetic energy from higher regions in the boundary layer towards the turbine level. In the current study, we investigate the use of optimal control techniques combined with Large-Eddy Simulations (LES) of wind-farm boundary layer interaction for the increase of total energy extraction in very large ‘infinite’ wind farms. We consider the individual wind turbines as flow actuators, whose energy extraction can be dynamically regulated in time so as to optimally influence the turbulent flow field, maximizing the wind farm power.

For the simulation of wind-farm boundary layers we use large-eddy simulations in combination with actuator-disk and actuator-line representations of wind turbines. Simulations are performed in our in-house pseudo-spectral code SP-Wind that combines Fourier-spectral discretization in horizontal directions with a fourth-order finite-volume approach in the vertical direction. For the optimal control study, we consider the dynamic control of turbine-thrust coefficients in an actuator-disk model. They represent the effect of turbine blades that can actively pitch in time, changing the lift- and drag coefficients of the turbine blades. Optimal model-predictive control (or optimal receding horizon control) is used, where the model simply consists of the full LES equations, and the time horizon is approximately 280 seconds. The optimization is performed using a nonlinear conjugate gradient method, and the gradients are calculated by solving the adjoint LES equations. We find that the extracted farm power increases by approximately 20% when using optimal model-predictive control. However, the increased power output is also responsible for an increase in turbulent dissipation, and a deceleration of the boundary layer. Further investigating the energy balances in the boundary layer, it is observed that this deceleration is mainly occurring in the outer layer as a result of higher turbulent energy fluxes towards the turbines. In a second optimization case, we penalize boundary-layer deceleration, and find an increase of energy extraction of approximately 10%. In this case, increased energy extraction is balanced by a reduction in of turbulent dissipation in the boundary layer.

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