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Noise and Vibration Issues of Wind Turbines and Their Impact - A Review

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This paper presents a systematic review of current literature on the issues of noise and vibration of wind turbines and their impact on human health and wild life. The paper reviews the literature on the issues of noise and vibration in wind turbines, the generation mechanisms, the propagation, the impact on human health and wild life. The current status of technology and future developments to mitigate the health and environmental impacts of wind turbine noise and vibration are also reviewed. The paper includes a review of current standards on measurement of acoustic noise of wind turbines and data analysis.

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Studying wind farm frequency regulation using high fidelity wind farm simulations

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Introduction: In the past, relatively insignificant installed wind power capacity meant that grid operators did not need wind power plants to participate in frequency regulation services. Over the past decade, however, wind power production has grown dramatically, with wind penetration levels exceeding 15% in several countries, such as Denmark, Portugal, and Spain [1]. As a result, grid operators are reevaluating frequency regulation requirements for wind farms. A number of system operators now require active curtailment of wind power for over-frequency regulation, and some system operators are also considering under-frequency regulation requirements for wind power plants [2].

Frequency regulation is provided by matching active power generation and demand over many time scales, ranging from seconds to hours, to maintain a stable grid frequency [3]. Recent studies have shown the feasibility of using stand-alone wind turbines for short- to medium-term frequency regulation by modulating the real power delivered through active power control [4, 5]. Active power control in wind farms, however, is complicated by aerodynamic interactions between turbines. When a wind farm changes operating conditions to provide frequency regulation, the wakes from upstream turbines will affect downstream wind conditions, thereby changing the power output of downstream turbines and potentially leading to unintended conse- quences. Therefore, a better understanding of these interactions is needed to develop effective controllers for wind farm frequency regulation.

In the current work, we study the use of wind farms for secondary frequency regulation, where participat- ing generators track a power production signal from the grid operator over a period ranging from minutes to an hour [3]. We propose using large eddy simulations (LES) [6, 7], a high fidelity simulation technique that numerically solves the filtered Navier-Stokes equations, coupled with the actuator line model (ALM) [8, 9]. This study is a first step towards demonstrating the usefulness of this approach, which allows for simulation of the aerodynamic impact of changes in the turbine operating state. First, we demonstrate that the qual-

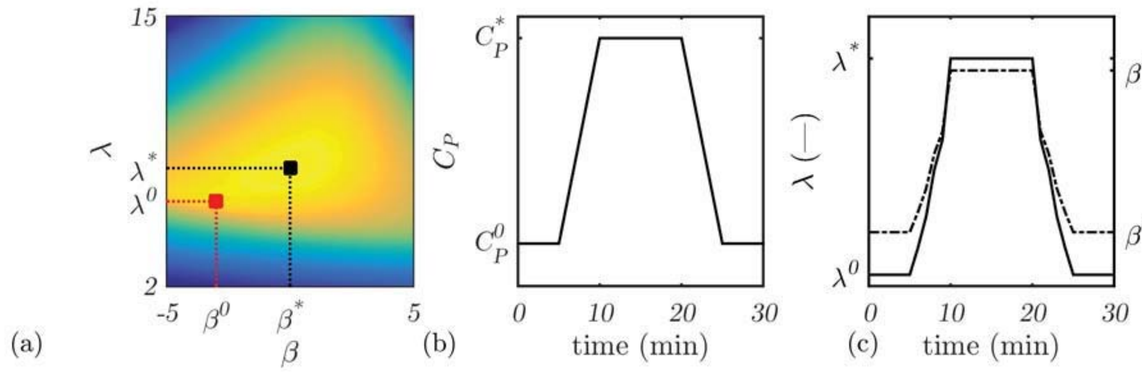

Figure 1: (a) Power coefficient curve as a function of tip speed ratio, λ, and blade pitch angle, β, showing both the optimal (black) and range of possible derated (red) operating conditions. (b) An example grid operator power generation signal, shown in terms of the power coefficient, and (c) a possible operating trajectory to follow this signal.

itative nature of the power coefficient curves used in prior active power control approaches for stand-alone turbines can be replicated with LES-ALM on relatively coarse grids. We then illustrate the large effect of changes in operating conditions on downstream power production and the potentially complicated nature of these effects. Finally we discuss the implications of these results in terms of the development of frequency regulation controllers.

Prior work: Secondary frequency regulation is achieved by taking advantage of power coefficient curves generated using simplified aerodynamic models [4, 5], for example based on blade element momentum (BEM) theory [10]. Traditional control strategies track an optimal power coefficient, C_P^*, that occurs at a unique optimal blade pitch angle, β^*, and optimal tip speed ratio, λ^* [11]. Secondary frequency regulation controllers operate at a derated state, C_P^0, β^0, and λ^0, which leaves room for increased power generation by moving to the optimal state [4, 5]. As an example, a hypothetical power coefficient curve is shown in Figure 1(a) with the optimal and derated operating states indicated on the axes. The wind turbine can follow a given power production signal provided from the grid operator, shown in Figure 1(b), by following a trajectory from the derated to optimal conditions, as shown in Figure 1(c).

LES-ALM power and thrust coefficients: In order to effectively study the impact of wake interactions and other turbulent flow characteristics on frequency controller efficacy, it is important to reproduce certain trends in the power and thrust coefficients of a real wind turbine. The power coefficient should have a unique optimal value, and the thrust coefficient should increase with increasing blade pitch angle and tip speed ratio. Given the relatively coarse grid resolution used in LES and the filtering of blade forces onto the LES grid, we need to employ a series of simulations to produce power and thrust coefficient curves for the LES-ALM system.

These curves are generated by simulating a NREL 5MW reference turbine [12] with a steady uniform inflow velocity $U_\infty = 8$ m/s in a domain with streamwise and spanwise lengths of 2.048 × 1.024 km and a grid resolution of $\Delta x = \Delta y = \Delta z = 8$ m. Blade pitch angles and tip speed ratios are varied from -4° to 6° and 6 to 10, respectively, to generate the power and thrust coefficient curves shown in Figure 2. These curves indeed replicate the qualitative behavior of curves generated from BEM theory. In particular, the power coefficients have a peak at an optimal tip speed ratio and blade pitch angle, and the thrust coefficients increase with increasing blade pitch angle and tip speed ratio.

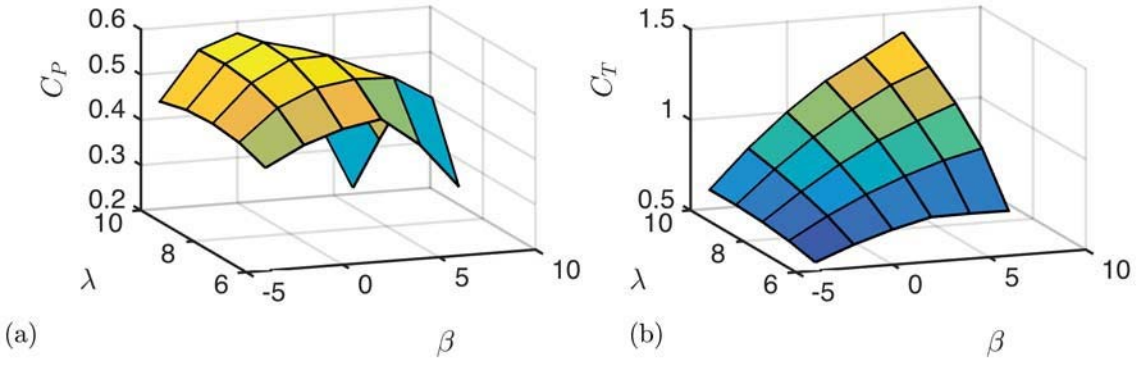

Figure 2: (a) Power and (b) thrust coefficients as function of tip speed ratio, λ, and blade pitch angle, β, generated with LES-ALM using an inflow velocity of $U_\infty = 8$ on grid with $\Delta x = \Delta y = \Delta z = 8$ m.

Turbine interactions: The effects of active power control on downstream turbines are studied in a small wind farm with 24 turbines arranged in 4 streamwise rows and 6 spanwise columns in a $\pi \times \pi \times 1$ km domain, as shown in Figure 3. Inflow conditions are simulated using a concurrent precursor simulation [6] of the atmospheric boundary layer with the same domain size and grid resolution. Starting at time $t = 0$ we change the blade pitch angle of the the turbines in the first row and look at the response of the downstream turbines. Three cases are investigated, $\beta = 1^\circ$, $\beta = -1^\circ$, and $\beta = -2^\circ$, and power production P for each case is compared to the power production of the control case P_c with no changes in blade pitch angle, as shown in Figure 4.

Pitching to feather (negative pitch angles) reduces the thrust coefficient, resulting in higher upwind

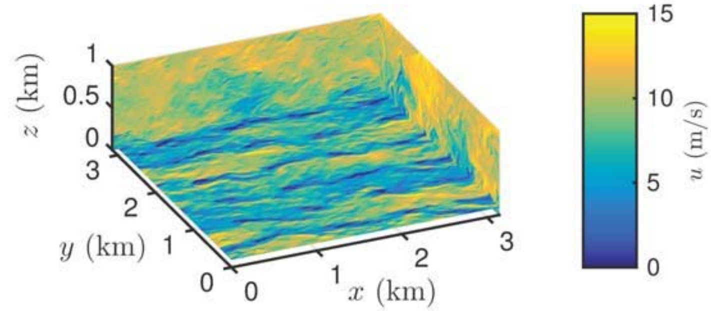

Figure 3: Streamwise velocity of wind farm with 24 turbines. Flow is in the positive x-direction, and wakes are clearly visible behind each turbine.

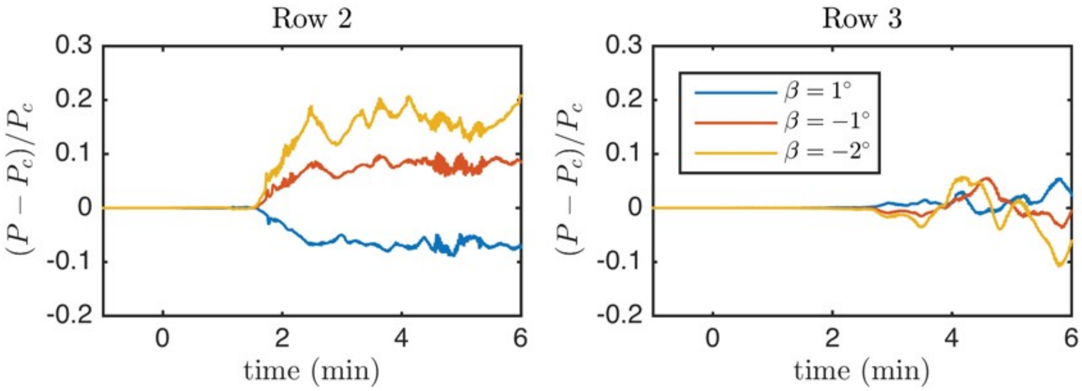

Figure 4: Average change in power production across each row P to the control case P_c for three treatment cases, where the first row of turbines are pitched to a set angle at $t = 0$.

velocities and power production for the downstream turbines. Conversely, pitching to stall (positive pitch angles) results in lower upwind velocities and power production for the downstream turbines. The change in power production for the downstream turbines has a time delay roughly equal to the convective time scale between turbines (i.e. the time that it takes for the wind to travel from one row to another). This time is 1.64 minutes for a hub-height velocity of roughly 8 m/s. Furthermore, the change in power output is large, corresponding to 10–20% of the power output in the control case.

These inter-turbine interactions will have interesting economic implications for wind farm frequency controllers. While the time delay between turbines could complicate frequency regulation control by reducing operational flexibility, the large relative effect of operational changes on downstream turbines could be leveraged to reduce the size of the steady-state derate (i.e. the difference between the operating power coefficient, C^{0}_{P}, and the optimal power coefficient, C_P^*) that is used to increase power production while providing frequency regulation service. Reducing the derate would have large economic benefits by increasing steady state power production when the grid operator does not call for frequency regulation services. Additional economic benefits could be realized through reduced structural loading caused by the control strategy.

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