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Effect of downwind swells on offshore wind energy harvesting – A large-eddy simulation study

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ABSTRACT

The effect of ocean downwind swells on the harvesting of offshore wind energy is studied using large-eddy simulation of fully developed wind turbine array boundary layers, which is dynamically coupled with high-order spectral simulation of sea-surface wave field with and without the presence of a downwind swell. For the two moderate wind speeds of 7 m/s and 10 m/s considered in this study, the swell is found to induce a temporal oscillation in the extracted wind power at the swell frequency, with a magnitude of 6.7% and 4.0% of the mean wind power output, respectively. Furthermore, the averaged wind power extraction is found to be increased by as much as 18.8% and 13.6%, respectively. Statistical analysis of the wind field indicates that the wind speed in the lower portion of the boundary layer oscillates periodically with fast wind above the swell trough and slow wind above the swell crest, resulting in the observed wind power oscillation. The wind above the swell accelerates due to the strong wave forcing, causes a net upward flux of kinetic energy into the wind turbine layer, and thus acts to increase the extracted wind power of the turbines. For a high wind speed of 17 m/s, the wave-induced motion becomes relatively weak and the swell effect on the wind turbine performance diminishes.

1. Introduction

With more available space, faster winds, and smaller visual impact and noise, offshore wind power has become a promising direction for wind energy and associated research. Offshore wind farms operate in a complex environment in which the sea surface is characterized by progressive waves of various sizes that interact with the wind over a wide range of scales. Therefore, the understanding of offshore wind farm dynamics and the predictions of wind turbine performance critically depend on the complex interaction among wind turbines, wind, and waves.

Previous studies on marine atmospheric boundary layer have shown that the characteristics of offshore wind are highly affected by its interaction with the sea-surface waves [1–4]. Among various types of sea-surface waves, the ocean swells play a distinct role. Generated by storms far away, swells can travel over long distance, enter the site of offshore wind farm, and mix with the local wind-seas (i.e., the wave field generated by the local wind). Because of the large amplitude and fast propagation speed, swells are capable of imposing strong disturbance to the marine wind field [3,5–7] and even generating wind under low and moderate wind conditions [8–10]. Thus, better understanding of turbine wake dynamics in offshore wind farms requires consideration of swell effect on wind.

In recent years, the combination of large-eddy simulation (LES) of atmospheric boundary layer and proper wind turbine models has made LES a useful tool for wind energy research [11–14]. For example, by performing LES of an "infinite" wind turbine array boundary layer, Calaf et al. [15] were able to capture the complex turbulent flow within a large wind farm as well as its expected interaction with the atmospheric boundary layer at large scales. Their LES results showed that inside a fully developed wind turbine array boundary layer, the wind field is energized for downstream wind energy harvesting through the vertical flux of kinetic energy from the atmosphere above.

While wind power on land is being actively explored, there has been a lack of LES tools for the simulation of offshore wind farms. Recently, a hybrid numerical capability has been developed by

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Yang et al. [16] for the simulation of large-scale offshore wind farms. The numerical framework consists of a LES of wind turbine array boundary layers on a curvilinear coordinate that follows the wave surface motion [17], and a spectral simulation of nonlinear sea-surface waves based on potential flow theory. The wind and wave simulations are dynamically coupled [18]. This simulation tool was shown to capture the effects of a broadband sea-surface wave field on the offshore wind farm dynamics [16]. In this study, we apply this hybrid simulation tool to study cases when swells are present.

In our simulation, a domain of 2.1 km long, 1.5 km wide, and 1.0 km high is considered. A 3 × 3 wind turbine array (aligned in both rows and columns) with periodic boundary conditions in the horizontal directions is used to model a fully developed “infinite” turbine array boundary layer [15,19–24], under neutral stratification. We note that some of the previous studies also considered wind turbine arrays with staggered or oblique arrangement, and found appreciable effect of the layout pattern on the performance of land-based wind farms [19,23,24]. Similar turbine array layout effect is expected for offshore wind farms. However, the presence of ocean swells is expected to induce qualitatively similar distortion on the wind field as the leading order effect for both the aligned and staggered turbines offshore. As a first attempt on investigating the swell effect, we focus on the aligned turbine array that has been used as the baseline case in most of the previous LES studies. The wind turbine effect is modeled by the actuator-disk model [11,12] with the effect of the turbine tower neglected as in most of the previous studies [15,19–22,24]. Among practical designs, many highly stable floating turbine platforms have only small motions under wind and wave forcing [e.g. Refs. [25,26]]. Although these small motions are still crucial for analyzing the structural response of the turbine system, they are not expected to induce significant effect on wind power generation. In this study, we focus on this type of highly stable platforms as a first step of the investigation, and thus treat the turbines as fixed in space (and as a result, the effect of mooring cables is also neglected).

Three different wind speeds, $U_{top} = 7.0$, 10.0, and 17.0 m/s (where U_{top} is the mean wind speed at the top of the simulation domain, 1.0 km above the mean sea surface), are considered. The sea surface has a broadband wave field. In addition, a swell propagating downwind is considered. In the simulation domain that is 2.1 km long, there are nine waves in the monochromatic swell train propagating in the streamwise direction, corresponding to a moderate wavelength of $\lambda_s = 233.3$ m. A typical steepness of $2\pi a_s/\lambda_s = 0.1$ is considered [4,9,27–29] so that the swell amplitude is $a_s = 3.7$ m. We remark that the problem can be further complicated by the fact that a swell can propagate in a different direction with respect to the local wind-seas. As the first attempt on the study of swell effect on offshore wind farms, we focus on the downwind swell condition that was investigated the most as a canonical problem in previous studies on wind–wave interaction [e.g. Refs. [8–10,30]].

Based on the simulation data, the effect of the downwind swell on the wind power extraction rate of the turbines is studied, with a focus on the swell-induced change in the mean value as well as temporal fluctuations. Statistical analysis of the offshore wind turbine array boundary layer is also performed to help understand the physical mechanism responsible for the swell effect.

This paper is organized as follows. First, the numerical method used in our hybrid model is introduced in Section 2, followed by an introduction on the problem setup and the parameters of the simulation cases. Next, the simulation results and data analysis are presented in Section 3 to show the swell effect on wind farm dynamics. Finally, conclusions are given in Section 4.

2. Numerical method

2.1. Large-eddy simulation of wind turbulence

Fig. 1 shows two typical examples of the instantaneous flow field in the offshore wind turbine array boundary layer obtained by the current simulation. In this study, we consider a neutrally stratified atmospheric boundary layer flow for the wind field. In LES, the motion of wind turbulence is described by the filtered Navier–Stokes equations for incompressible flows

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho_a}\frac{\partial \tilde{p}^*}{\partial x_i} - \frac{\partial \tau_{ij}^d}{\partial x_j} - \frac{1}{\rho_a}\frac{\partial p_\infty}{\partial x}\delta_{i1} + f_T\delta_{i1}, \quad (1)$$

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0. \quad (2)$$

As shown in Fig. 1, the coordinates are denoted as $x_i (i = 1,2,3) = (x,y,z)$, where x and y are the horizontal coordinates and z is the vertical coordinate, with $z = 0$ being the mean sea surface. The velocity components in x-, y-, and z-directions are denoted as $u_i (i = 1,2,3) = (u,v,w)$, respectively. In Eqs. (1) and (2), $\widetilde{(\dots)}$ indicates filtering at the grid scale Δ; ρ_a is the density of air; $\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i\tilde{u}_j$ is the subgrid-scale (SGS) stress tensor, and τ_{ij}^d is its trace-free part; and $\tilde{p}^* = \tilde{p} + \tau_{kk}/3 - p_\infty$ is the filtered modified pressure. In this study, we consider the condition of mean wind being perpendicular to the wind turbine rotor plane, i.e. along the $+x$-direction. The imposed pressure gradient $\partial p_\infty/\partial x$ models the effect of geostrophic wind forcing [15].

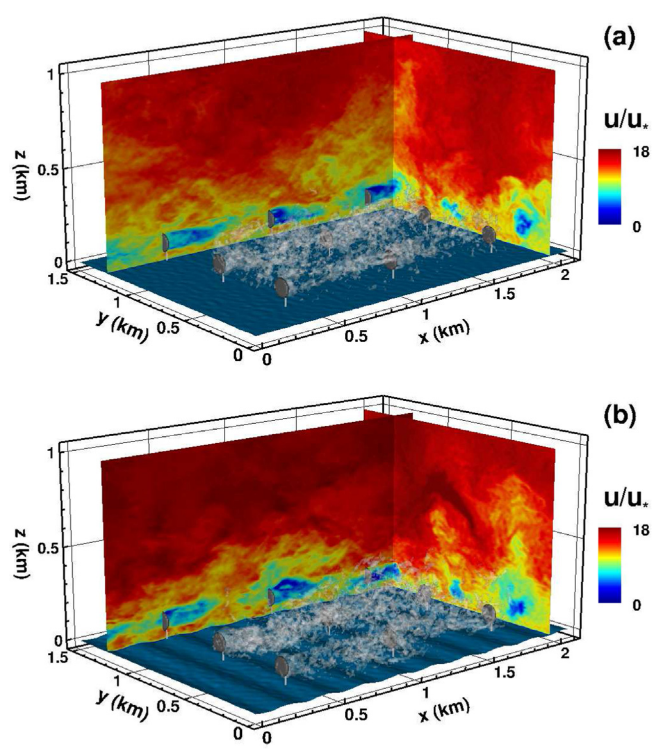

Fig. 1. Flow field in a fully developed wind turbine array boundary layer at sea for $U_{top} = 10$ m/s with: (a) pure wind-seas; and (b) wind-seas mixed with swells. Contours of instantaneous streamwise velocity u (normalized by u_*) are plotted on two representative (x,z)- and (y,z)-planes. The turbulent wakes behind the first four wind turbines are illustrated by the iso-surface of the normalized vorticity magnitude $|\omega|/(u_*/D) = 20$. Here, U_{top} is the mean wind velocity at the top of the simulation domain; u_* is the wind friction velocity above the turbine array; ω is the vorticity; and D is the turbine rotor diameter.