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Wake to wake interaction of floating wind turbine models in free pitch motion: An eddy viscosity and mixing length approach

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ABSTRACT

Experiments were performed using two model wind turbines operated in tandem with a bottom-fixed configuration and a floating configuration with both turbines allowed to freely oscillate in the streamwise direction. Wakes of both turbines were measured using stereoscopic Particle Image Velocimetry. Turbulent characteristics of the far wake of the first turbine acting as the inflow for the downwind turbine were characterized calculating the eddy viscosity and mixing length profiles from the obtained data. The influence of the far wake on the statistical properties of the near wake of the second turbine are compared between the fixed and oscillating configurations. The incoming mixing length clearly influences the Reynolds stresses and turbulence production of the near wake in the shear layer. Below, the connection between incoming mixing length and the near wake is less evident, due to the impact of the nacelle and rotation of the rotor. For the oscillating turbine, the Reynolds stresses and turbulence production in the near wake of the downwind turbine are damped. Vertical fluctuations were found to decrease though an increase in the mean vertical component. New challenges arise in the design of a floating offshore wind farms, in terms of farm layout and load estimations.

1. Introduction

Wind energy is a major contributor to the renewable energies. To fulfill the increasing demand of power, wind turbines are operated in farms. The implementation of wind farms onshore is limited due to space constraints, therefore application of offshore wind turbines also in deep water is of interest [1]. For areas where no shallow water (<50 m) is available, several concepts have been developed for floating offshore wind turbines. Floating constructions add degrees of freedom to the system in comparison to onshore wind turbines.

In particular the interaction of wind turbines via wakes shows the need of a deeper knowledge of the wake development of wind farms for reliable operation and power prediction. Experimental studies were performed using model wind turbines operated in wind tunnels, where the influence of turbulent inflow conditions as well as atmospheric boundary layer stability on the performance of the turbines and on the wake development were investigated [2–9]. Generally, higher turbulence levels in the wake were found to increase momentum transport from undisturbed surrounding flow and enhance wake recovering. Hancock [10] and Zhang [11] found convection in the boundary layer to facilitate the recovering of the wake due to enhanced moment transport. Investigation on the influence of tip speed ratios of the model wind turbine on the near wakes vortex structures were performed [6]. The evolution of the tip vortex structures and their interaction under uniform inflow were found to drive the mixing process in the wake, thus the recovery of the wake [12]. Incoming turbulence intensities on loads of a model turbine and the development of the near wakes turbulent structures have shown that higher incoming turbulence intensity results in higher turbulent kinetic energy and stresses in the wake, which enables faster recovering of the wake flow [13]. Zhang et al. [14] analyzed the near wake of a model wind turbine under different stratifications of the boundary layer using stereoscopic particle image velocimetry. Khosravi et al. [15] performed comparative wind tunnel experiments to investigate the effect of platform surge motion. They found a slight increase in power production of the moving turbine when compared to a stationary and also a decrease in Reynolds shear stress, with the conclusion of

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a weaker recovering of the wake in the floating case. Experimental and numerical [16,17] investigations of floating turbines in surge motion have shown an increase of thrust and power variations with increasing tip speed ratios of the turbines, with good agreement of experimental and numerical results for rated tip speed ratios and below. Sebastian et al. [18] performed numerical investigations on unsteady aerodynamics of floating wind turbines and found the pitch motion of a floating platform being one major contributor to unsteady flow effects. This paper deals with the case of floating wind turbines and the impact of the platform pitch motion on the wake.

In assuming a steady, incompressible and inviscid flow in a wind turbine array, the momentum balance for such flow is given by the Reynolds-averaged Navier–Stokes (RANS) equation as,

$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} - \frac{\partial \overline{u_i u_j}}{\partial x_j} - F_{x_i}, \qquad (1)$$

with U_i being the mean velocity components and u_i its fluctuations. Where the overbar denotes ensemble averages, $x_1 = x$ the streamwise, $x_2 = y$ the vertical and $x_3 = z$ the spanwise directions. The air density is given by ρ, the mean pressure by P and F_{x_i} is the thrust force by the turbine, which mainly acts in the streamwise direction [3,9,19,20].

The vertical transport of kinetic energy in the wake region is connected to the Reynolds shear stress by the mean kinetic energy equation, which is given by,

$$U_j \frac{\partial \frac{1}{2} U_i^2}{\partial x_j} = -\frac{1}{\rho} U_i \frac{\partial P}{\partial x_i} + \overline{u_i u_j}\frac{\partial U_i}{\partial x_j} - \frac{\partial \overline{u_i u_j} U_i}{\partial x_j} - U_i F_{x_i}. \qquad (2)$$

This closes the energy budget by balancing the convection of the mean kinetic energy of the flow to the mean pressure gradient, the production of turbulence kinetic energy, the gradient of kinetic energy flux and the power extracted by the turbine, respectively. Here we denote U_i as U,V,W and u_i as u,v,w respectively.

Averaging of the Navier–Stokes equation yields the Reynolds stress, which may be modeled to solve the RANS equation. This can be achieved using the Boussinesq hypothesis [21], which is stated as,

$$\overline{uv} = -\nu_t \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right), \qquad (3)$$

with ν_t being the eddy viscosity. A classical generalized model for the eddy viscosity on the basis of the mean strain rate tensor is given by the relation:

$$\nu_t = l_m^2 \sqrt{\frac{1}{2}\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right)^2} = l_m^2 \cdot S, \qquad (4)$$

using a mixing length l_m and the characteristic strain rate S [21]. Based on equations (3) and (4), ν_t and l_m can be obtained from $\partial U_j / \partial x_i$ and $\overline{uv}$; the latter two being measurable quantities. The model is widely used in meteorological descriptions like for canopy flows, e.g. to describe turbulent processes in the boundary layer above forested terrains [22,23]. The concept was used by Bai et al. to characterize the development of the wake flow behind a fractal tree and was found to be suitable in the description of transverse momentum fluxes [24]. The approach of describing the Reynolds stress using the eddy viscosity is also applied in the context of wind energy application, where it is in part used in the *Dynamic Wake Meandering Model (DWD)*, which is a computationally inexpensive tool to describe wake effects [25].

Herein, the eddy viscosity and mixing length are calculated from data measured in wind tunnel experiments. These characteristic quantities are used to describe the turbulence in the far wake of a fixed and an oscillating turbine and its influence on the near wake of a second turbine positioned downwind as these act as an inflow condition. In the following, the experimental setup, the measurement planes as well as the SPIV settings will be described. Then, a characterization of the inflow conditions of the downwind turbine for the fixed and floating case in comparison to the freestream inflow is given. This is done by calculating the eddy viscosity and profiles of the mixing length from the measured SPIV data. Finally, conclusions on the mixing length and on implications for offshore floating wind farms are drawn.

2. Setup

In this section an overview of the facilities, the model wind turbines and used SPIV setup will be given.

2.1. Wind tunnel and model wind turbines

Experiments were performed in the closed-circuit wind tunnel at Portland State University, which has a cross section of 0.8 m × 1.2 m and a test section of 5 m in length. The inflow conditions can be varied from 2 m/s to 40 m/s at a low turbulence level (cf. [7]). An image of the setup is provided in Fig. 1 as well as a schematic view of the wind tunnel as well as the experimental setup is presented in Fig. 2. In order to achieve atmospheric-like conditions, a passive grid was used to introduce a turbulence level of 9% and vertical strakes were used to shape the inflow velocity profile. Further details on the inflow characteristics can be found in Ref. [20], where measurements were performed to observe the differences in the wake of a fixed *versus* a pitching single wind turbine; these results were then compared to various wake models. Here, a second wind turbine was positioned in the wake of the upwind turbine at a distance of 7.5D. The turbines have a rotor diameter of 0.2 m, a nacelle with a diameter of 28 mm and a cylindric tower with a diameter of 16 mm. Hub height of both turbines was set to $hh = 0.24$ m. The turbines are mounted in gimbal supports which allow oscillations in streamwise direction and are stabilized by cylindrical weights. The position of the weight of the first turbine was chosen in such way that the turbine is allowed to oscillate with respect to the incoming flow. As a consequence of the inflow, the oscillation of the first turbine is around 16°–19° with a frequency range of 1.2–1.8 Hz [20]. Same setting for the stabilizing weight was chosen for the downstream turbine, which resulted in a reduced range of angles of 3°–5° for the oscillations and a frequency range of 0.7–0.9 Hz due to lower

Fig. 1. Photography of experimental facility and model wind turbines (downwind view).