Brief Communication: On the influence of vertical velocity profiles on the combined power output of two model wind turbines in yaw

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Abstract. The effect of vertical velocity gradients on the total power output of two aligned model wind turbines as a function of yaw misalignment of the upstream turbine is studied experimentally. It is shown that asymmetries of the power output of the downstream turbine and the combined power of both with respect to the upstream turbine's yaw misalignment angle can be linked to the vertical velocity gradient of the inflow.

1 Introduction

Lately, different concepts of active wake control are discussed throughout the research community. One promising concept is the wake deflection by intentional yaw misalignment of single wind turbines. The principle of deflecting the velocity deficit behind a wind turbine was observed in field measurements by Trujillo et al. (2016), in wind tunnel experiments (e.g. Medici and Alfredsson, 2006; Krogstad and Adaramola, 2012) and in numerical simulations (e.g. Gebraad et al., 2014; Vollmer et al., 2016). Further, Gebraad et al. (2016) applied the concept to wind farm control strategies, showing a potential power increase in wind farm applications.

Vollmer et al. (2016) and Gebraad et al. (2014) report on an asymmetric deflection of a turbine's wake with respect to its direction of yaw misalignment. Fleming et al. (2014) and Gebraad et al. (2016) showed that only one direction of yaw misalignment resulted in a power increase of a two turbine array, while the exact opposite direction caused a power decrease. This finding has been confirmed by Schottler et al. (2016a) experimentally using two model wind turbines. As those findings impact the applicability of the concept significantly, reasons for the asymmetry need to be understood.

Vollmer et al. (2016) studied the influence of atmospheric stabilities on the wake deflection by yaw misalignment. The results showed that different stratifications indeed resulted in varying deflections of the wake behind the rotor of a numeric turbine model. More precisely, disparities between wake deflections due to yaw misalignments of $+30°$ and $-30°$ were significantly different considering different atmospheric stratifications and therewith different vertical velocity gradients. It is believed that a combination of a vertical inflow gradient, the wake's rotation and the wind veer cause asymmetric wake deflections with respect to the rotor's yaw angle. In this study, we show that a vertical velocity gradient has a direct effect on the wake's asymmetry during yaw misalignment using two model wind turbines in a wind tunnel study.

2 Methods

The experiments were performed at the University of Oldenburg. Two model wind turbines as described by Schottler et al. (2016b) were used in streamwise displacement. The turbines where separated by $3D$, with $D = 0.58$ m being the rotor diameter. The upstream turbine is placed on a turning table allowing a yaw misalignment, while the downstream turbine utilizes a partial load control and therewith adapts to the changing inflow conditions. Further details about the setup are described by Schottler et al. (2016a). In order to isolate the effect of a vertical velocity gradient in the inflow, the horizontal axes of an active grid at the wind tunnel outlet were set statically to create two different inflow profiles, which were characterized prior to the experiments. 13 hot wire probes were used simultaneously in a vertical line arrangement with a distance of 75 mm separating two sensors. For both settings of the grid, data were recorded for 120 s at a sampling frequency of 2 kHz. The downstream position of the hot wire array was 1 m from of the wind tunnel outlet, in agreement with the upstream turbine's rotor, which was installed after characterizing the inflow. Fig. 1 shows mean wind speeds over the height z, whereas z = 0 m corresponds to the bottom of the wind tunnel outlet. The reproducibility of time averaged velocity profiles for one grid setting has been investigated and confirmed. Further, mean values have been checked for statistical convergence. As of now, we refer to the inflow conditions
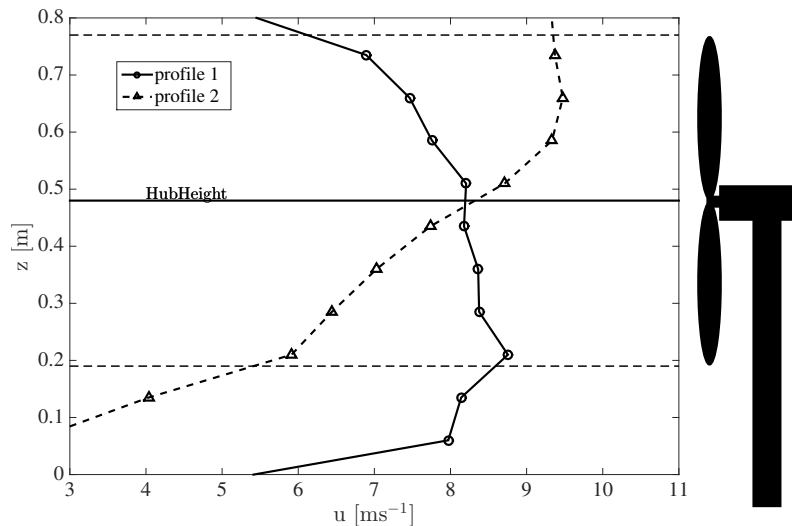

Figure 1. Mean velocity values of the vertical wind speed profiles profiles 1 and 2 that were used as inflow conditions. The dashed, vertical lines mark the heights of the rotor tips of the turbine that was installed after characterizing the inflow profiles.

shown in Fig. 1 as *profile 1* and *profile 2*. Using two inflows which feature a vertical velocity gradient in opposite direction allows an investigation of the gradient's influence on the asymmetric power output of the two turbines with respect to the upstream turbine's yaw angle, γ_1.

3 Results

Mean values of the combined power P_{tot} and the power of the downstream turbine P_2 are shown for every examined yaw angle γ_1 in Fig. 2. For each curve, data points are normalized to the respective maximum. Looking at 2(a), asymmetries of both
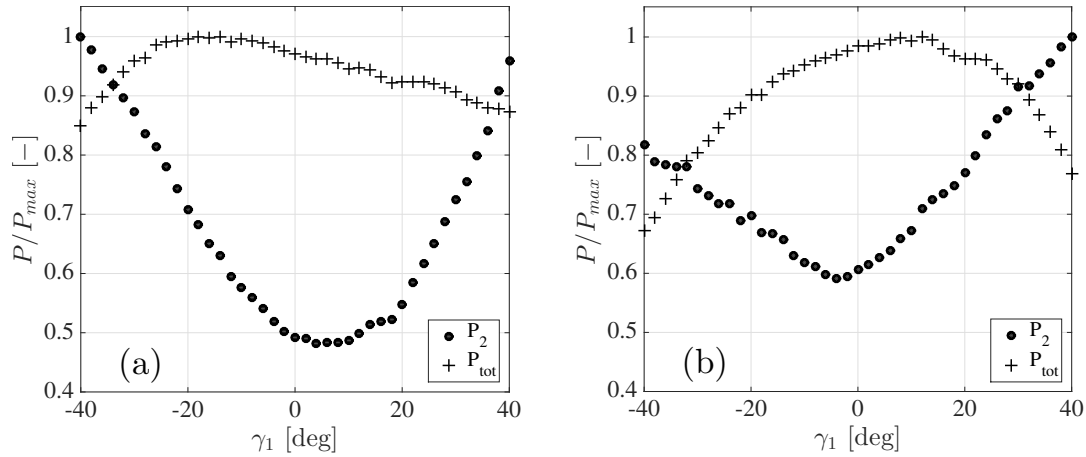

Figure 2. Mean values of P_2 and P_{tot} for each examined value of γ_1 during the both inflow condition profile 1 (a) and profile 2 (b).

curves with respect to γ_1 become obvious. The minimum of the downstream turbine's power P_2 is shifted towards positive

5 angles. The combined power P_{tot} is maximal at $\gamma_1 \approx -18°$, being approx. 4 % larger compared to the case with perfect yaw alignment $\gamma_1 = 0°$. Also the combined power shows a distinct asymmetry with respect to γ_1. While the power is maximal at $\gamma_1 \approx -18°$, it further decreases for larger values of γ_1. For positive yaw angles the total power output is smaller compared to the case of no yaw misalignment. The results support that the direction of a purposeful yaw misalignment is of great relevance regarding the application of this concept to wind farm control. Further, the general shape of the graphs is in good agreement

10 with numeric simulations of full size turbines reported by Fleming et al. (2014).

Fig. 2(b) shows the results of the same experiment, whereas nothing but the inflow conditions was changed to profile 2. Since the reproducibility of results was proven by Schottler et al. (2016a), the effect of the changed inflow is isolated. As can be seen, asymmetric shapes of both graphs are still observed. More importantly, the direction of the asymmetry changed with the direction of the inflow's vertical velocity gradient. Now, in Fig. 2(b), the minimum of P_2 is located at negative yaw angles,

15 $\gamma_1 \approx -4°$. Also for the total power output, the sign of the maximum's location changed, being positive ($\gamma_1 \approx 12°$) during inflow profile 2. Our results suggest, that the reason for the asymmetric shapes of the graphs in Fig. 2 is related to the inflow velocity gradient, which is further discussed in Sec. 4.

4 Discussion and conclusion

In this study, we investigate the influence of vertical velocity gradients on the power output of two aligned model wind turbines. An asymmetry of the power output with respect to the upstream turbine's yaw angle was found in prior experiments on laboratory scale (Schottler et al., 2016a) as well as in full scale numeric simulations (Fleming et al., 2016; Vollmer et al., 2016),

5   whereas the causes were not fully understood. With the present methods, we further investigate the reasons for the asymmetric wake deflection and isolate the effect of a vertical inflow gradient's orientation on the power output of a two turbine array. A strong linkage between the asymmetry and the velocity gradient's orientation was found. For a potential application of active wake control by intentional yawing, the effect itself needs to be understood. If the reported asymmetry depends on boundary conditions of the surroundings, which our results suggest, than this drastically impacts the applicability to real world wind

10   farm control scenarios. In this study, the downstream turbine is used and conclusions about the wake deflection of the upstream turbine is based on power measurements. The interesting results regarding the asymmetry and its linkage to the inflow conditions motivate further examinations in detailed wake measurements during different inflow gradients and yaw errors. The vast majority of model wind turbine experiments face a Reynolds number mismatch between the laboratory and full scale case, which is nearly a factor of 170 in this study. However, due to the good agreement of the general shape of the turbines' normal-

15   ized power comparing the present study and Schottler et al. (2016a) with simulations of a full scale case (Fleming et al., 2014; Gebraad et al., 2014), the Reynolds number dependence is assumed to be rather insignificant when judging general effects of wake deflection.

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