Experimental testing of wind turbine wake control

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Abstract

An experimental wind tunnel study on the interaction of two model wind turbines exposed to different turbulent inflows is presented. This study investigates the applicability of the basic control variables tip speed ratio, pitch angle and yaw angle under different inflow conditions and serves as a databank of well-defined reference cases at model scale. Results indicate that the total power can be increased for large yaw angles at the expense of a significant increase in yaw moments on both upstream and downstream turbine. Furthermore it is shown that small variations in the upstream turbine's tip speed ratio or pitch angle keep the total power output rather constant while mitigating the rotor thrust effectively.

Keywords: *Experimental scale simulations, wake modeling, wind turbine interaction*

Introduction

Wake interactions between the single turbines are estimated to cause power losses between 10-20% in large offshore wind farms [1]. Instead of controlling for each individual turbine's optimum power output, holistic wind farm control approaches are currently discussed in science. A reduction of the axial induction on the front row turbines increases the available kinetic energy in the wake that can be recovered by the downstream turbines. This can either be done by changing the tip speed ratio or reducing the blade pitch angle. Another option for wind farm power optimization is an intentional yaw misalignment by which the trajectory of the wake is deflected.

Methods

In this experimental wind tunnel study the effects of controlling an upstream turbine's tip speed ratio, pitch and yaw angles on the mean and turbulent wake flow are studied for different turbulent inflows. Furthermore, the interaction of the wake with a downstream rotor is analysed with respect to power output and thrust and yaw moment loads on a downstream turbine. The experimental setup comprises two model wind turbines (D=0.90m, λ_{opt}=6.0, NREL S826 airfoils) which are set up in an in-line arrangement. By the means of turbulence grids the inflow to the two turbine setup is varied from an inflow of low turbulence (TI_A=0.2%), high turbulence (TI_B=10.0%) and a non-uniform sheared inflow of high turbulence (TI_C=10.0%). In order to characterize the inflow conditions for a downstream turbine, mean and turbulent wake characteristics are measured in a full plane x/D=3 and x/D=6 downstream with a Laser-Doppler-Anemometer (LDA).

Results

While a reduction in tip speed ratio is observed to leave more energy in the outer part of the rotor swept area, a reduction in blade pitch angle uniformly adds kinetic energy over the entire rotor swept area (Fig 1.b). Controlling the tip speed ratio of the upstream turbine away from its design point does not prove to significantly benefit to the combined array efficiency. Only for low background turbulence or small turbine separation distances the energy lost on the upstream turbine can be recovered by the downstream turbine (Fig.2.a). Slightly lower combined efficiencies are observed for pitch control (Fig.2.b). Both induction-based wake control strategies are observed to effectively pass along thrust loads from the upstream turbine to the downstream turbine while the total power output is almost kept constant.

Yaw misalignment of the upstream turbine, however, causes a cross-stream thrust component, which laterally deflects the wake (Fig.1 a & b). The stream-wise mean wake flow is observed to form a curled-shaped velocity deficit at higher downstream distances. A comparison of the wake center deflection with models by Jimenez et al. [2] as well as Bastankhah and Porté-Agel [3] show a better agreement of the latter of those. The degree of wake center deflection is observed to be slightly dependent on the inflow turbulence level; however, to a smaller degree as predicted in Bastankhah and Porté-Agel's wake model.

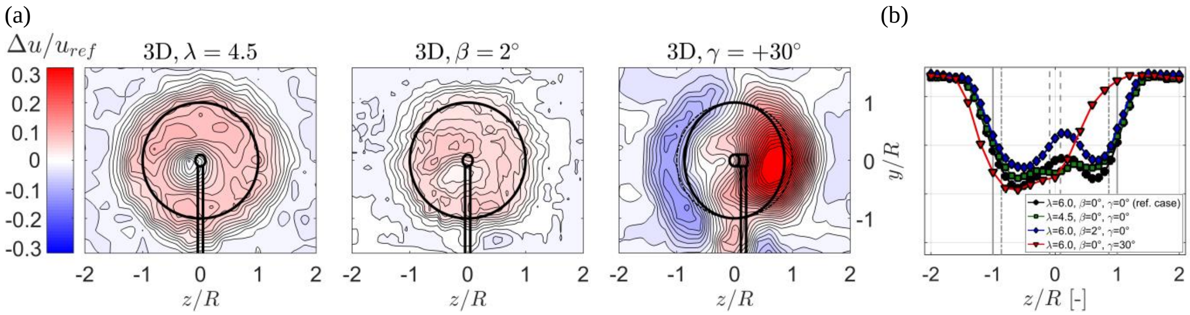

Figure 1: (a) Added mean velocity $\Delta u/u_{ref}$ in the wake x/D=3 downstream of the turbine T1 by λ-control, β-control and γ-control of the upstream turbine. (b) Mean velocity profiles u/u_{ref} at the turbine hub height at x/D=3. The inflow is uniform (TI_B=10.0%).

Gains in total power by yaw control are observed to increase with higher turbine separation distances as the wake is further deflected (Fig.2.c). For an inter-turbine spacing of x=6D and a yaw angle of γ=30°, gains of about 8% compared to the non-yawed reference case are measured for this model scale wind tunnel setup. The power increase is observed to be asymmetric with respect to upstream turbine yaw angle. This asymmetry is in agreement with studies by Gebraad et al. [4] and Schottler et al. [5], who observed similar effects for turbines turning the other way round. The gains in total power are however, to the expense of highly unsteady loads on the upstream and downstream rotor as demonstrated by measurements of mean yaw moments.

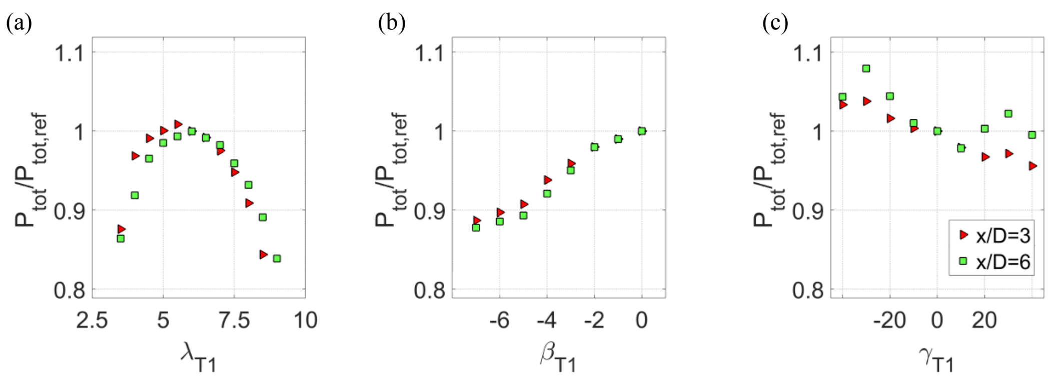

Figure 2: Relative total power of the two-turbine array for (a) λ-control (b) β-control and (c) γ-control of the upstream turbine. The separation distance is x/D=3 respectively x/D=6. The inflow is uniform (TI_B=10.0%).

Conclusions

It is demonstrated that the total power can be increased for large yaw angles with a significant simultaneous increase in yaw moments on upstream and downstream turbine. The deflection of the wake center is to a small degree observed to be dependent on the inflow turbulence level. An asymmetry in total power output for positive and negative yawing of the upstream turbine is observed. Slight variations in tip speed ratio or pitch angle are observed to almost keep the total power output constant, and at the same time are able to effectively mitigate rotor loads.

References

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