Impact of flow inclination on downwind turbine loads and power

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Abstract. Wind turbines frequently operate under situations of pronounced flow inclinations, such as in complex terrain. In the present work the performance and rotor thrust of downwind and upwind turbines in upward and downward flow inclinations are experimentally investigated. In an upward flow inclination of +13°, downwind turbines are shown to have a 29% larger power output than a corresponding upwind turbine, whereas the relative increase in rotor thrust is only 9%. Furthermore, it is also shown that the performance of downwind turbines is less sensitive to changes in the flow inclination, as the upstream nacelle on downwind turbines beneficially redirects and accelerates the flow around the nacelle into the rotor plane.

1. Introduction

As the global installed wind capacity continues to grow, there is increasingly limited availability of flat terrain for the installation of wind farms. Thus, there is a need to exploit the wind resource in complex terrain, even though there are challenges such as transportation, connection to the grid, and elevated ambient turbulence, for wind farms in complex terrain. As the rotor is oriented downstream of the nacelle, downwind turbines have several advantages over upwind turbines. Firstly, as the nacelle anemometer is upstream of the rotor, the measured flow is free from interference of the rotor’s wake, which improves reliability in the operation of the turbine. Secondly, downwind turbines are inherently stable in yaw, which improves the orientation of the rotor relative to the incoming wind direction [1]. Furthermore, the blockage effect of the downwind turbine’s nacelle accelerates and redirects the incoming flow into the rotor, resulting in up to 3% higher power for a downwind turbine compared to an upwind turbine [2]. There are previous experimental studies in which the effect of an incoming flow that is inclined relative to the horizontal on wind turbine aerodynamics and performance has been examined [3, 4]. However, these studies have examined, respectively, vertical-axis wind turbines and horizontal-axis upwind turbines; there are no prior studies of downwind turbines in inclined flow. Given the increased interest in the use of multi-megawatt downwind turbines, it is necessary to fill this knowledge gap. While there have been several efforts to model the effects of flow inclination on turbine performance, for example [5, 6], in which the reduced power output of a turbine in inclined flow is modeled as a function of the deviation angle between the inflow and the rotor axis, a comprehensive experimental database will aid the further development of improved models. The goal of the present work is to quantify the impact of flow inclination on the loads and performance of downwind turbines. In order to put this impact in its proper context, this
experimental study compares the loads and output power of downwind and upwind turbines in inclined flow.

2. Experimental Setup
This experimental study is conducted in the ETH wind turbine test facility, WEST Facility, (Figure 1). The WEST Facility consists of a 40m long, 1m wide and 1m deep water tank over which a carriage is moved. The model turbine is installed on the carriage. In the WEST Facility, with the use of water instead of air as the test medium, the Reynolds numbers are a factor 15 closer to the Reynolds numbers on full-scale turbines. Upstream of the model, counter-flowing jets are used to inject water perpendicular to the carriage motion in order to generate an inflow turbulence intensity of 8%. The model turbine is a 1:160 scale of the Hitachi 2MW downwind turbine (Figure 1). More complete details of the model can be found elsewhere [1], but for sake of completeness some salient details are provided here. The model is of a modular design, and the rotor, of diameter 0.5m, may be configured to be either downwind or upwind. The ratio between the nacelle blockage area and the rotor swept area is approximately 2%, which is more than the ratio of approximately 0.5% on the full-scale turbine. The model is installed on a platform on which the incoming flow’s inclination $\phi$ relative to the turbine can be varied. As can be seen in Figure 2 an upward flow inclination $\phi$ of the incoming flow is defined as positive, and vice versa. Following common practice in turbine design the model has a tilt angle $\theta$ and a cone angle $\alpha$ of 8° and 5°, respectively, as on the Hitachi 2MW downwind turbine.

Figure 1. ETH wind turbine test facility (left) and Hitachi 2MW downwind turbine (right, courtesy of Wind Power Ltd.)
Figure 2. Schematic illustration of flow inclination $\phi$. Positive flow inclination (left) and negative flow inclination (right) on downwind (left) and upwind (right) turbines, respectively. Also shown are positive tilt angles $\theta$ and cone angles $\alpha$ on both turbine configurations.

The shaft torque is measured through a custom-built in-line torque meter and the rotor thrust is simultaneously measured from strain gauges that are mounted on the tower. Both the torque and thrust are sampled at 10kHz, thus providing measurements of both the steady and unsteady loads and performance. The measurement uncertainties in the derived power and thrust coefficients are less than $\pm 2.0\%$. Details of the model and the experimental test matrix are summarized in Table 1.

| Test matrix                  |
|-----------------------------|
| Rotor orientation           | downwind, upwind          |
| Flow inclination $\phi$     | -12°, ±8°, ±4°, 0°, +13° |
| Rotor tilt $\theta$         | 8°                        |
| Rotor cone $\alpha$         | 5°                        |
| Tip speed ratio TSR         | 0.9TSR$_{opt}$, TSR$_{opt}$, 1.1TSR$_{opt}$ |

3. Results

In the following the effect of flow inclination on the downwind turbine’s power output, rotor thrust and shaft torque unsteadiness are compared to the upwind turbine. Thereafter the sensitivities of the power outputs to the operating point are discussed for downwind and upwind turbines for upward and downward flow inclinations and in horizontal flow.

3.1. Effect of flow inclination on performance and loading

Figures 3 and 4 compare the effect of flow inclination on power and thrust of downwind and upwind turbines; in this case the turbines are operated at the optimum tip speed ratio (TSR$_{opt}$). For sake of clarity, the power and thrust coefficients are normalized relative to the power and thrust coefficient of the downwind turbine in zero flow inclination. As shown in [2], in zero flow inclination, the downwind turbine has approximately 3% more power and larger thrust than the upwind configuration. In Figures 3 and 4 it can be seen that for non-negative flow inclinations the downwind turbine has higher power output and higher thrust, whereas for negative flow inclinations of more than -8° the upwind turbine has a larger power output than the downwind turbine. For the positive flow inclination
of $+13^\circ$, the downwind turbine has 29% larger power output than the upwind turbine, while the thrust is only 9% larger for the downwind turbine. By comparison the model of [6] predicts a 21.5% larger power output for the downwind turbine in a $+13^\circ$ inclined flow. On the other hand, for a downward flow inclination of $-12^\circ$, the upwind turbine has a 7% larger power output than the downwind turbine, whereas the thrust is the same for both rotor configurations.

**Figure 3.** Comparison of effect of flow inclination $\phi$ on power of downwind and upwind turbines. The power coefficients are normalized relative to the power coefficient of the downwind turbine in zero flow inclination.

**Figure 4.** Comparison of effect of flow inclination $\phi$ on thrust of downwind and upwind turbine. The thrust coefficients are normalized relative to the thrust coefficient of the downwind turbine in zero flow inclination.
A comparison of the inclined flow into the rotors of downwind and upwind turbines, (Figure 2), clarifies the observations in Figures 3 and 4. The rotors of multi-megawatt downwind and upwind turbines are tilted in order to maximize the clearance between blades and tower. This tilt leads to an orientation of the rotor such that the rotor plane is more perpendicular to the incoming flow with positive flow inclinations for downwind turbines, whereas the opposite is the case for upwind turbines. Thus, it may be anticipated that on downwind turbines there is a more favorable orientation of the rotor, compared to upwind turbines, for non-negative flow inclinations. Accordingly, in complex terrain where the flow is inclined upwards relative to the horizontal, downwind turbines will outperform upwind turbines. On the other hand, when the flow is inclined downwards relative to the horizontal, there is a potential advantage of upwind turbines compared to downwind turbines. However, this advantage is limited, as on downwind turbines the nacelle has a tendency to better orient the flow to the rotor plane. This better orientation of the flow to the rotor is a consequence of the nacelle’s favorable blockage effect that accelerates the flow adjacent to the nacelle and into the rotor plane [2].

Figure 5 compares the effect of flow inclination on the unsteadiness of the shaft torque on downwind and upwind turbines. The unsteadiness is measured in terms of the ratio of the standard deviation of the unsteady torque to the mean shaft torque. The turbine operating point is at optimum tip speed ratio. The measured unsteadiness of the shaft torque is larger for the downwind turbine. However, as the flow inclination is increased from -12° to +13°, the unsteadiness of the shaft torque increases by 42% for the upwind turbine compared to an only 11% increase for the downwind turbine. This observation is consistent with the substantially reduced aerodynamic performance of upwind turbines in large upward flow inclinations as opposed to pronounced downward flow inclinations (Figure 3).

**Figure 5.** Comparison of effect of flow inclination $\phi$ on shaft torque unsteadiness

While the broadband unsteadiness in the shaft torque that is shown in Figure 5 provides an overview of the total load variations, it is instructive to also take into consideration at which frequencies those load variations occur. In this regard two frequencies are of specific interest. Firstly, the blade passing frequency. Variations of the shaft torque at this frequency are related to characteristic interactions between the blades and the tower wake or potential flow field and furthermore related to azimuthal variations of the blade loading over one rotation of the rotor. This frequency plays a dominant role, when the turbine is operating as intended. The other frequency is the characteristic frequency at which vortices are shed from the blade. For the present experiment this
frequency is around 160Hz, which is equivalent to a Strouhal number of 0.2 [7]. Excessive vortex shedding from the blade is a sign of reduced aerodynamic performance of the blade, and can accordingly be expected when there is an unfavorable alignment between inflow and rotor axis.

Figures 6 and 7 illustrate the effect of flow inclination $\phi$ on the unsteadiness at the blade passing and vortex shedding frequencies. The unsteadiness is quantified as the ratio of the variance at the respective frequency to the shaft torque variance for the downwind and the upwind turbine respectively. As it was previously reported elsewhere for zero flow inclination [7, 8], the unsteadiness at the blade passing frequency accounts for a larger share of the overall shaft torque unsteadiness on the downwind turbine than on the upwind turbine for all tested flow inclinations. Whereas the unsteadiness at the blade passing frequency is most pronounced for zero and slightly positive flow inclinations, there is a clear increase of the unsteadiness at the frequency of vortex shedding from the blade for the largest positive and negative flow inclinations. This effect is observed for both rotor orientation; however it is more pronounced on the upwind than on the downwind turbine. The relative increase in the contribution of the vortex shedding frequency for the largest flow inclinations can be expected as these flow inclinations have the largest misalignments between the axes of the blade normal and the inflow of 20° and higher and the wind aerodynamic performance of the wind turbine blades degrades. As the turbine blades are no longer aerodynamically loaded as intended and undesired three-dimensional flow phenomena gain in importance, a relative decrease of load variations at the blade passing frequency together with a simultaneous increase of vortex shedding from the blade are a consequence. On the other hand, for moderate flow misalignments of up to 15° relative to the blade normal, the desired loading on the blade is established over the rotor rotation leading to the characteristic oscillations of the load at blade passing frequency. The less pronounced increase of vortex shedding from the blade on the downwind turbine (Figure 6) together with the reduced sensitivity of the downwind turbine power output to changes in flow inclination (Figure 3) both suggest an improved suitability of the downwind turbine for situations with large flow inclinations.

**Figure 6.** Effect of flow inclination $\phi$ on relative contribution of blade passing and vortex shedding frequencies to the variance of the shaft torque on the downwind turbine
3.2. Interdependency between flow inclination and operating point

Wind turbines operating in unsteady flow fields with pronounced flow inclinations that are typically observed in complex terrain are likely to experience deviations from the optimum operating point. The combined and interacting effects of flow inclination and operating point on downwind and upwind turbine performance are next discussed. Figure 8 provides a comparison of the performances versus tip speed ratio of downwind and upwind turbines for upward flow inclinations of 8°. For all operating points, the downwind turbine has a 21% - 33% higher power output than the upwind turbine.
Figure 8. Comparison of power of downwind and upwind turbine for flow inclination $\phi$ of $+8^\circ$. The power coefficients are normalized relative to the power coefficient of the downwind turbine at $\text{TSR}_{\text{opt}}$.

In Figure 9 the power outputs of the downwind and upwind turbines are compared for a downward flow inclination of $8^\circ$. While the upwind turbine has a higher power output at optimum tip speed ratio, its power output is lower than the output of the downwind turbine at below optimum tip speed ratio. In flow without inclination the downwind turbine yields a larger power output than the upwind turbine for optimum and non-optimum operation points (Figure 10).

Figure 9. Comparison of power of downwind and upwind turbine for flow inclination $\phi$ of $-8^\circ$. The power coefficients are normalized relative to the power coefficient of the downwind turbine at $\text{TSR}_{\text{opt}}$. 
4. Conclusions

A detailed experimental study has been conducted to assess the effects of flow inclination on a downwind turbine; for comparison measurements are also made on an upwind turbine. It is observed that in upward flow inclination, that is a characteristic of the flow in complex terrain, downwind turbines have a larger power output than upwind turbines. While the increased power is accompanied by an increase in the rotor thrust, the relative increase in thrust is less than the relative increase in power. The better orientation of the downwind turbine’s rotor relative to the inclined flow explains this advantage in the performance of the downwind turbine. There is a less pronounced increase of vortex shedding from the blade on the downwind turbine compared to the upwind turbine in flow fields with pronounced flow inclinations. Together with the reduced sensitivity of the downwind turbine’s output power to changes in flow inclination, this work indicates that downwind turbines are better suited than upwind turbines for application in complex terrain with upward flow inclination.

5. References

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