NEAR FLOW MEASUREMENTS USING NACELLE LIDARS: THE FUTURE OF POWER PERFORMANCE?

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Summary

An innovative method using a nacelle lidar measuring close to the rotor has been developed to assess power performance. This breaks with tradition in that measurements are taken between 0.3 and 1.2 rotor diameter. Yet the new method is able to yield probably the best possible estimate of free stream wind speed. This is achieved by fitting a simple induction model to the nacelle lidars' measurements at multiple ranges. Based on a 7-month measurement campaign in flat terrain, we demonstrate how this method allows robust determination of free stream wind speed. Such an estimation of free stream wind speed is key to power performance verification particularly for situations where it cannot be measured (e.g. in complex terrain or within an offshore array). Results show very promising comparison between a power curve obtained using a traditional mast at 2.5 rotor diameter and the one obtained using lidar reconstructed free stream wind speed.

1 Introduction

1.1 Use of profiling lidars to assess power performance

It has been shown that ground-based profiling LIDARs can improve power performance assessment by measuring simultaneously at different heights [1]. Contrary, although they are unable to measure wind shear, two-beam nacelle lidars show promising capabilities in assessing power performance [2]. The use of nacelle lidars could offer a considerable economic advantage by removing the need to erect meteorology masts, especially offshore. A new generation of commercially developed profiling nacelle lidars combines the benefits of both (Fig. 1).

Fig. 1: 5-beam Avent Demonstrator (left) and ZephIR Dual Mode (right) in Høvsøre, Denmark.

1.2 Definition and measurements of free wind speed

Power performance standards require to measure the free stream wind speed. Free stream is undisturbed e.g. from obstacles, or from the influence of neighbouring turbines or the turbine of interest itself. IEC 61400-12-1:2005 defines the free stream wind speed as the <u>horizontal component of the free wind speed that would exist at the position of the center of the turbine's rotor if the turbine were not present</u>. Free stream is commonly measured using a meteorological mast and cup anemometers located at 2.5 rotor diameter upstream.

2 Near flow measurements for power performance testing

2.1 Why measuring close to the rotor?

Free stream wind rarely exists in an offshore array and is hardly measurable in complex terrain. Additionally, for a rotor size of 150 m, the free stream is at a distance of 375 m. Two major issues arise:

- Loss of correlation: free stream wind measured 375 m upstream reaches the turbine's position in ~40 seconds;
- Extinction of lidar's signal: low signal-to-noise ratios observed at longer distances, inducing lower quality measurements.

Near flow measurements combined with knowledge of induction from wind turbines can be used to accurately estimate free stream wind speed. By measuring closer to the rotor, the induction effects appear to prevail on other disturbances such as terrain.

2.2 The Nørrekær Enge campaign

A 7-month measurement campaign was conducted in 2015 in Nørrekær Enge (NKE), Denmark. In NKE, the 5-beam Avent Demonstrator (5B) and ZephIR Dual-Mode (ZDM) lidars were installed on the nacelle of a Siemens 2.3 MW turbine featuring a rotor diameter D_{rot} of 93 m. An IEC compliant met. mast is used for reference measurements of power curves. Fig. 2 shows the configuration of the measurement ranges of both lidars together with the position of the met. mast.

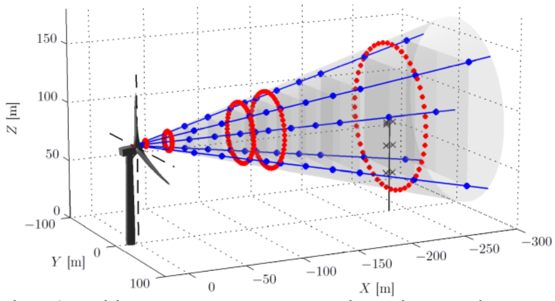

Fig. 2: Lidars' measurement trajectories and range configuration in NKE: 5B (blue) and ZDM (red).

Prior to the measurement campaign, the two lidars have been calibrated at DTU's test site for large wind turbines in Høvsøre [3]. Thus, traceable measurements are obtained.

3 Free wind reconstruction and power performance assessment

3.1 Wind field reconstruction in free stream

Wind lidars can estimate various wind characteristics by taking advantage of their measurement principles. Primarily, a lidar senses backscattered light from particles moving with the wind. Line-Of-Sight (LOS) velocities are then inferred from Doppler spectra. The LOS velocities and beam positions data are finally used to estimate wind characteristics using a model-based approach [4].

The model-based reconstruction estimates wind characteristics by fitting simulated LOS velocities to real measurements in an iterative process:

1. A wind model is defined based on starting values for the wind characteristics.
2. LOS velocities are simulated at the measurement locations using the wind model.
3. Simulated LOS velocities are compared to the measured ones.
4. Iterations are performed to minimise the error between simulated and measured LOS velocities.

This method corresponds to those implemented for example in ground-based lidars. In power performance, no time dependency is considered: the wind model is applied to 10-minute averaged LOS velocities.

NKE is in flat terrain. The retained wind model is an inhomogeneous flow assumed to have no vertical component (two-dimensional). Additionally, vertical wind shear is considered through a power law profile. Three wind characteristics are thus reconstructed for each 10-minute period: horizontal wind speed at hub height, yaw misalignment and shear exponent. Estimations of hub height "free stream" wind speed were obtained by applying this reconstruction model at the 2.5 D_{rot} range.

3.2 Wind field reconstruction combined with simple induction model

A simple one-dimensional induction function obtained from the Biot-Savart law [5] is implemented within the reconstruction (steps 1 to 3 in 3.1):

$$\frac{V}{V_\infty} = 1 - a\left[1 + \frac{\xi}{\sqrt{1+\xi^2}}\right],$$

where V_∞ is the free stream wind speed, a is the induction factor (cf. actuator disk theory) and $\xi = 2x/D_{\mathrm{rot}}$, x being the upstream coordinate in the hub reference frame. The inhomogeneous flow model previously described is thus combined with the induction model. The induction factor can be set to a reasonable value or added as a new degree of freedom. Then, The wind characteristics and thus outputs of the reconstruction are V_∞, yaw misalignment, shear exponent and induction factor.

3.3 Power curves verification and AEP

The turbine's performance is verified by comparing the power curves obtained from the mast and from the lidars using three methods:

1. Measurements in the free stream, at 2.5 D_{rot};
2. Measurements in the induction, at 1.0 D_{rot}, and a correction to the free wind with an induction factor a of 0.3;
3. Measurements at multiple ranges located between 0.3 and 1.2 D_{rot} combined with fitted induction characteristics V_∞ and a.

For each method, the Annual Energy Production (AEP) was calculated using Rayleigh wind speed distributions. The results demonstrate the validity of using near flow lidar measurements to estimate free stream wind speed as required for power performance assessment.

4 Conclusion and learning objectives

In this paper, we demonstrate how nacelle lidars' near flow measurements can be used to reconstruct wind characteristics relevant for power performance.

A full scale 7-month campaign provides the data to test several methods for free stream wind speed estimations. The first method employs free stream measurements and is applicable in flat terrain. The second and third methods combine near flow measurements with an induction function. The newly developed methods prove to be accurate and results show a reduction in the scatter of the power curves obtained from the lidars compared to the one obtained from an IEC compliant mast.

Using near flow measurements opens the path towards accurate power curve measurements in any type of terrain: this new method will be further tested within the UniTTe project (www.unitte.dk) with two measurement campaigns in complex terrain. The improved accuracy in power performance assessment based on nacelle lidar near flow measurements has potential to reduce uncertainties in AEP. Nacelle-mounted profiling lidars might very well be the future of power performance.

References

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