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Power performance measured using a nacelle lidar

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Abstract

Wind turbine power performance requires the measurement of the free wind speed at hub height upstream of the turbine. For modern multi-megawatt wind turbines, this means that the wind speed needs to be measured at great heights, from 80m to 150m. The standard wind speed measurement with a cup anemometer, requiring the erection of a tall met mast, then becomes more and more challenging and expensive. A forward looking lidar, mounted on the turbine nacelle, combines the advantages of a nacelle based instrument - no mast/platform installation difficulties - and those of the lidar technology - remote measurement of the wind speed away from the instrument.

In this paper, we present results of an experimental campaign aiming at developing testing procedures that meets the requirements of the power performance standard IEC 61400-12-1 with a nacelle-based lidar. A nacelle-lidar prototype was installed on the nacelle of a multi-megawatt wind turbine at Risø DTU test site for large wind turbines. This lidar is a pulsed system emitting alternating signals in two horizontal lines of sight, symmetrical about the rotor axis.

The power curves obtained with the lidar measurements and the mast were compared. The results show less scatter in the power curve for the nacelle-based lidar measurements than for the mast measurements. A nacelle-based lidar is always aligned with the turbine orientation, so it constantly measures the upstream wind speed. This assures a better correlation with the wind encountered by the turbine rotor than the wind measured by a cup anemometer on a mast or a ground based lidar.

1 Introduction

Ground-based wind lidars have progressed in reliability and performance to the point where good systems measure with comparable accuracy to mast-mounted cup anemometers [1]. Power performance measurements have also been demonstrated with ground-based lidars, where the additional profile information, when represented in an equivalent wind speed, can reduce the power curve scatter [2]. An obvious next step is the logistically attractive solution of moving the wind lidar on to the wind turbine nacelle and measuring the horizontal wind speed approaching the rotor using a (near) horizontal lidar beam. If this technique proves to be sufficiently accurate and practical, the need for measuring masts in conjunction with power performance (and other) measurements could be reduced. This would have huge cost benefits, especially offshore.

This paper describes a power curve measurement performed with a prototype nacelle-lidar, an adapted version of the successful Leosphere WLS-7. As a first step, the nacelle-lidar is used to measure the incoming flow at hub-height only. In order to be accepted within the wind community, the measurement must be performed in as close conformity to the current IEC 61400-12-1 standard [3] as possible. This has been a central and governing theme in the campaign. In particular, since the lidar is no longer completely fixed in space but is mounted on the flexible wind turbine, it is important to ensure that the standard's requirements on measuring height are respected. An additional factor that is investigated is the partial obscuration of the beam by the blades of the wind turbine and how this can affect the accuracy of the measurements.

In the following sections we will describe the experimental setup and calibration of the lidar. Comparisons of power curves measured using standard hub-height anemometry and the nacelle lidar are then presented and conclusions are drawn.

2 Experimental set up

The lidar used in this measurement campaign was designed by Leosphere specifically to be mounted on a turbine nacelle and to measure the wind speed at hub height. It is a pulsed system able to measure at 50m to 300m from the turbine. The laser emits a stream of pulses in two lines of sight, resulting in radial speeds (projection of the wind speed along the line-of-sight) in two different directions alternatively. The two lines of sight are separated by a horizontal angle of 30 degrees. The horizontal wind speed is retrieved from two consecutive radial speeds. Two line-of sights are required to recover the two components of the horizontal wind speed but requires us to assume that the wind speed is horizontally homogeneous.

The lidar was mounted on a multi- megawatt (MW) wind turbine at Risø DTU's Test Site for Large Wind Turbine, at Høvsøre, on the western coast of Denmark. On the west side of the turbine, at a distance equivalent to two rotor diameters (2D), stands a hub height mast equipped with a top mounted cup anemometer.

The lidar was aligned with the main shaft of the turbine, so that the lines of sight were positioned symmetrically around it (15 degrees on each side), see figure 1.

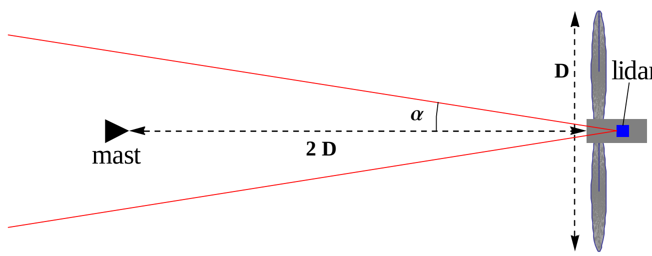


Figure 1: Top view sketch of the experimental set up. The red lines show the lines of sight relative to the turbine axis (black dashed line). D is the rotor diameter, α is the horizontal angle between the turbine axis direction and the line of sight (half beam angle). α=15° in this set up.

Moreover since the lidar was mounted on top of the nacelle, somewhat above hub height, the lidar was inclined by 0.6 degrees downwards, thereby measuring at hub height at a distance of 2.5 D in front of the turbine when it is stopped, in order to comply as much as possible with the IEC standard 61400-12-1 [3] requirements for measurement height tolerances. As the thrust on the rotor increases, the tower bending acts to lift the lidar beam. In order to monitor this distortion, two inclinometers were placed in the lidar, on the plate supporting the laser optical bench and were carefully calibrated prior to the mounting. The inclinometers are used both to orientate the lidar at the correct downward inclination at installation and to monitor the lifting of the beam due to tower bending during wind turbine operation.

3 Results

3.1 Comparison lidar/cup

First, the horizontal wind speed measured by the lidar at 2D, i.e. about same distance as the mast, was compared to that measured by the cup anemometer. Only the western wind sector is considered here, defined so the laser beam is not in the wake of the neighbouring wind turbines. In order to select a dataset usable for power curve measurement, only the data when the turbine was operational were selected.

Finally, 10 minute data with abnormally high CNR (carrier to noise ratio), showing that the laser beam of the lidar has hit the mast, as well as data with very low availability (below 30%), meaning that most of the stream of pulses were blocked by the turbine blades, were discarded. This filtering, based on lidar data quality, removed only 1.5% of the data.

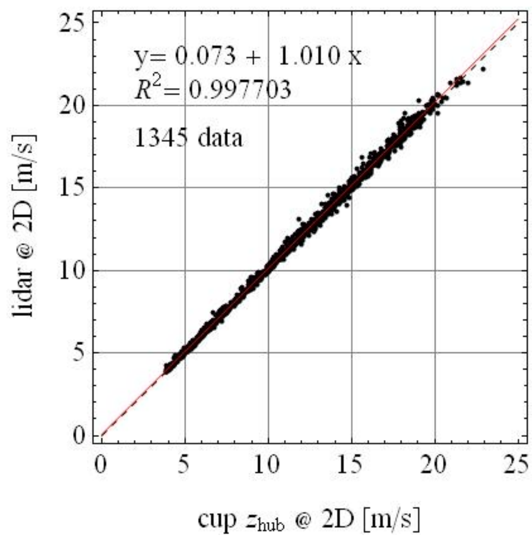


Figure2: Comparison of the horizontal wind speed measured by the lidar at a distance of 2 rotor diameters in front of the turbine with the wind speed measured by the mast top mounted cup anemometer.

The horizontal wind speed measured by the lidar compares well to that of the cup anemometer. However, the lidar overestimates the cup anemometer measurements by 1% on average. The effect of the blade blocking the laser beam was found to influence the availability of the lidar data within 10 minutes but was not shown to affect significantly the lidar error (i.e. difference with the cup anemometer). The tilt and roll of the nacelle modifies the vertical angle of the lines of sight and therefore the measurement height. The lidar/nacelle tilt and roll were recorded with the inclinometers placed in the lidar for a part of the measurement campaign. However, the range of variations of these two angles was very limited. The tilt was estimated to induce a variation in the measurement height up to 4m above hub height. This can result in a significant lidar error in case of large wind shear but cannot explain 1% overestimation in the wind speed on average by itself. This error (within the usual range of wind lidars) is therefore suspected to be due to the combination of several parameters, related to both the lidar and the cup anemometer properties and needs more investigation.

3.2 Power curve for westerly winds

Using exactly the same dataset as that shown in figure 2, we derived the power curve obtained with the cup anemometer on one hand and the power curve obtained with the lidar on the other hand. Both bin-averaged power curves are shown in Figure 3 They are very similar. The main difference is a slight shift of the lidar power curve to the right, which is the consequence of the 1% overestimation of the wind speed noticed in section 2.1.

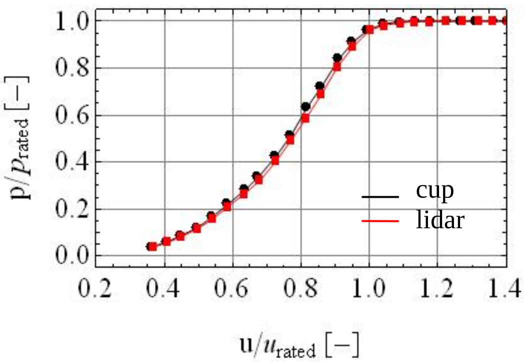


Figure 3: Bin-averaged power curves obtained with the lidar measuring at 2D and the mast top mounted cup anemometer.

The power curve scatter plots obtained with each instrument are displayed in figure 4. These two graphs were plotted with the same scale. We can see that the power curve obtained with the lidar (figure 4(b)) has a smaller scatter than that measured by the cup anemometer(figure 4(a)). The difference in scatter here is due to the correlation between the free wind speed measured at 2D upwind to the turbine and the wind speed at the wind turbine rotor from which the power is extracted. Indeed, for the wind speed measured with the cup anemometer, this correlation is maximum when the wind blows from the mast toward the turbine and decreases as the wind direction deviates from this line. As the lidar is fixed to the nacelle and aligned with the turbine axis, it always measures the wind coming towards the rotor. Therefore the correlation remains high as long as both lines of sight are measuring in the free homogeneous wind. The difference in scatter appears clearly in figure 4 as the wind sector considered here is much larger than normally used for power performance measurement which is usually restricted to a 90degrees sector, due to the fixed position of mast.

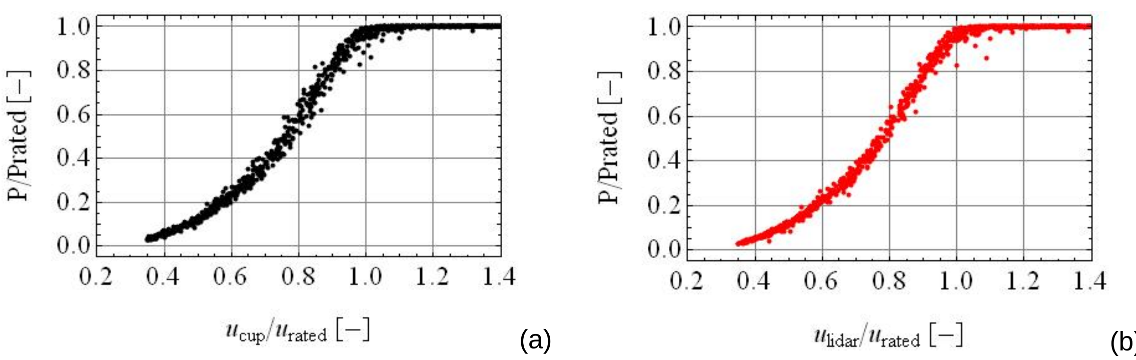
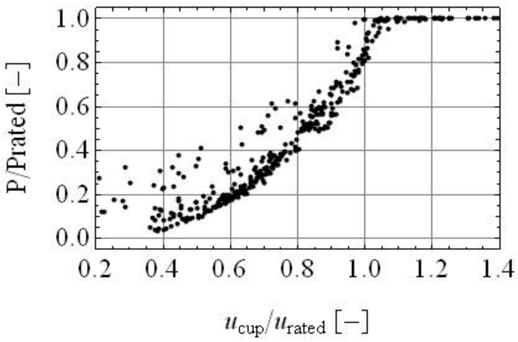


Figure 4: Power curve scatter plot (10 min mean data) with wind speed measured by the mast top mounted cup anemometer (a) and by the lidar at 2D (b) for the westerly wind sector.

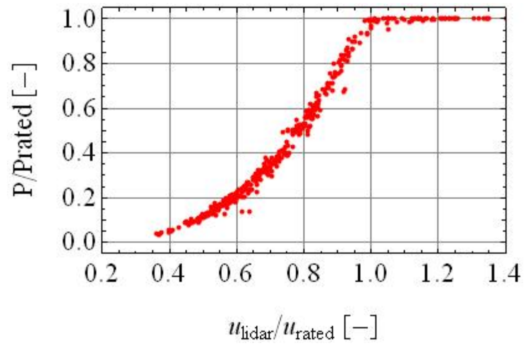
The decrease in scatter in the power curve can be interpreted as a decrease in a statistical uncertainty in the power curve measurement. However the total/combined uncertainty of the power curve measurement also depends on the wind speed measurement uncertainty which remains to be defined and evaluated for the lidar.

3.3 Power curve for easterly winds

The turbine considered in this measurement campaign is located within a row of 5 turbines oriented North-South. This turbine is therefore in the wake of other turbines when the wind comes from the north and from the south. However the eastern sector is free of obstacles. We also performed a power curve measurement for this wind sector. The same filtering criteria were used for the data selection as for the western sector. As shown in figure 5, the power curve obtained with the cup anemometer contains many outliers because the cup anemometer, located on the west side of the turbine, is disturbed by the wake of the turbine under test. The lidar, on the other hand, is measuring in front of the turbine (towards east), therefore in the free wind. The power curve obtained with the lidar has a scatter comparable to that obtained for the western sector (see figure 5 (b)).



(a)



(b)

Figure 5: Power curve scatter plot (10 min mean data) measured by the mast top mounted cup anemometer (a) and by the lidar at 2D (b) for the easterly wind sector.

Moreover the power curve measured by the lidar for the western and the eastern sector, are very similar after bin-averaging, as shown in figure 6.

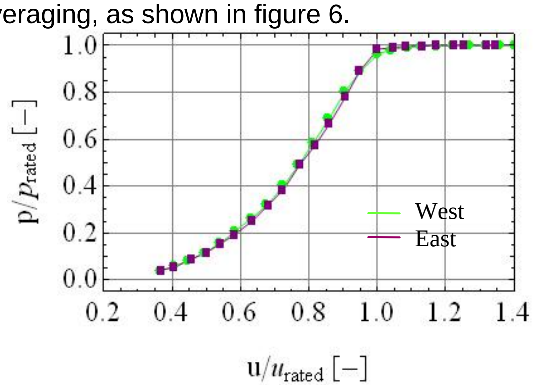


Figure 6: Bin-avearged power curves measured by the lidar at 2D for the western sector and the eastern sector.

4 Conclusions

A nacelle lidar, having two lines of sight, was tested for power performance measurement on a multi-MW wind turbine. The comparison of the wind speed measured by the lidar, measuring at a distance of two rotor diameters, to a hub-height cup anemometer, located at the same distance from the turbine, showed good agreement. However the wind speed was overestimated by 1% by the lidar and this needs further investigation.

The lidar measurements resulted in a power curve comparable to that measured by the cup anemometer for the westerly sector (where the mast is not disturbed by any wake). As the lidar follows the turbine yawing, the wind speed measured by the lidar is better correlated to the wind speed at the turbine rotor position than the wind speed measured by the mast and the scatter in the power curve is smaller for the lidar power curve.

A power curve was also measured for easterly wind with the lidar, which in contrast to the mast, still measures in the free wind in this configuration. The power curve obtained was comparable to that for the west sector. These two results demonstrate one of the main advantages of such an instrument for power performance: a larger wind sector can be used to achieve a power curve measurement than with a mast. Moreover the correlation between the wind speed measured away from the turbine (free wind) and the wind speed from which the power is extracted by the rotor is much less wind direction dependant than the cup anemometer. This implies that a complete power curve can be achieved, without the use of a measuring mast, in a shorter period of time and probably with a smaller statistical uncertainty.

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