Wind speed measurement for absolute power curve determination from induction zone lidar measurements

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Abstract. There is growing interest in turbine performance assessment using nacelle mounted lidars. In the past, this has involved measuring the free stream wind speed, on the periphery of the operating turbine’s induction zone. As turbines increase in size, measuring at correspondingly longer ranges can start to introduce uncertainties in the wind speed, especially in complex terrain or when a turbine is part of an array. One way of reducing these uncertainties is to measure wind speeds inside the turbine’s induction zone, closer to the turbine’s rotor, then use various techniques to adjust these measurements to generate free stream equivalent windspeeds. This paper describes the application of both induction zone model and transfer function approaches. The results from various campaigns are presented and the two methods are compared using correlations. Both yield good results in terms of accuracy (usually gradients of 1.00 ± 0.004) and coefficients of determination (typically 0.99).

1. Introduction

Absolute power curves require the free stream wind speed to be determined. Usually this is measured, to a good approximation, at 2.5 rotor diameters (D) upstream of the wind turbine, as described in IEC 61400-12-1. Nacelle mounted lidars are often used, as they offer significant advantages over meteorological masts or ground lidars. However, as a wind turbine’s rotor diameter increases in size, the upwind measurement distance increases proportionally. At these longer ranges there are two potential sources of additional measurement uncertainty: 1) the wind field can evolve significantly as it approaches the turbine, especially in complex terrain, and 2) if the turbine forms part of a large array, then measurement of wind speed at 2.5D and beyond can overestimate the turbine’s true free stream value, due to the array blockage effect – note that the free stream wind is the wind speed that would exist at the position of the centre of the turbine’s rotor if the turbine were not present. These uncertainties occur irrespective of the measurement technology. As a result of this situation, the concept of relative power curves was introduced. Here wind speed measurements are made inside the induction zone, closer to the turbine. The resulting relative power curves can be useful, but do not give a direct measure of absolute turbine performance. However, several studies have extended the idea by using measurements made inside the induction zone to estimate the free wind speed, compensating for induction effects, thereby allowing results equivalent to absolute power curve to be made.

The general approach was the impetus for Project UniITTe [1], and results from the project were encouraging [e.g. 2]. A subsequent IEA sponsored activity [3] used a nacelle mounted lidar dataset as a basis for exploring various methods of back propagation of lidar measurements, made in the induction
zone, to yield projected free stream wind speeds upwind of the turbine. The methods included using various induction zone models and computational fluid dynamics (CFD) techniques. Comparisons of analyses by industry and academia indicated generally a high level of consensus on the results [4].

This paper presents the results of analyses of more recent campaigns. The measurements were made using nacelle-mounted, circular-scan, multi-range CW lidars on a variety of sites and turbine sizes. The lidar scan half-cone angle was 15°. Both analytic wind models and empirical approaches were used to convert the induction zone lidar measurements to calculated wind speeds at the extremities of the induction zone. In each case, the individual turbines were sufficiently isolated that array effects could be neglected. These calculated wind speeds were then compared with actual measurements at that range, and correlation analyses performed.

2. Objectives
The objectives of the work presented here are to add further evidence for the veracity of the general approach of measuring turbine performance by using measurements inside the induction zone. It is hoped that this will add impetus to industry efforts to refine these techniques, with the goal of eventual inclusion in best-practice guides and relevant industry standards.

3. Methodology
3.1. 1D induction model
The principle of this approach was to perform nacelle mounted lidar measurements of the incoming wind field, at multiple ranges inside the turbine’s induction zone. Ten-minute hub height wind speed averaged quantities were used, with data filtering to remove complex flow (as measured by the lidars) and atmospheric effects e.g. low cloud and hill fog (also measured by the lidars), as described in [5]. The complexity of the flow was determined by calculating the least-squares deviation of the line-of-sight windspeeds measured by the lidar and those predicted by the lidar’s wind field reconstruction model. Filtering was also performed to only include ten-minute periods where the turbine was operating normally. Additional sector filtering was sometimes applied when analysis included comparisons made with fixed ground lidars or meteorological masts.

For each of the ten-minute periods, an induction model was used to perform a least squares fit of the lidar wind speed measurements. In this way, the free parameters in the induction model were determined. Measurement ranges based on the configurations described in [6] were used to inform the lidar measurement. For the results reported here, the Medici 1D induction zone model [7] was used. This has parameters of free wind speed ($u_\infty$) and induction factor ($\alpha$). The induction factor is a measure of the strength of the induction, or blockage effect. The model used was:

$$\frac{u}{u_\infty} = \left(1 - \alpha \left(1 - \frac{\zeta}{\sqrt{1 + \zeta^2}}\right)\right)$$

where $u$ is the horizontal wind speed at any upstream axial point in the induction zone and $\zeta$ is the range upwind of the rotor, normalised by the rotor radius. Figure 1 illustrates the typical measurement arrangement used.
Figure 1. Left: a typical measurement layout for the induction zone model reconstruction approach. The turbine rotor diameter in the figure is 94 m. Right: Circular scanning CW lidars were used in these studies.

From $\alpha$ and $u_{\infty}$ for each 10 minute period, $u_{2.5}$ (the hub height wind speed at 2.5 D) were then calculated. These model-derived wind speeds were then compared to actual measurements at this range, allowing correlation plots or power curves to be constructed.

3.2. Empirical transfer function method
The other technique discussed in this paper is the empirical approach. This is akin to the existing procedures for calibrating conventional nacelle mounted anemometry to estimate upwind windspeeds at 2.5 D [8]. In a similar way to which nacelle transfer function corrected turbine anemometry can be used to measure a turbine power curve, a lidar wind speed measurement close to the turbine can also be used.

A quality-filtered (as described in section 3.1) lidar data set containing (typically) 30 m range measurements was compared with concurrent measurements at 2.5 D ranges. The resulting empirical transfer function was then applied subsequently to other 30 m measurements from other turbines of the same type to estimate the 2.5 D wind speed ($u_{2.5}$).

Figure 2. Measurement configuration for the transfer function determination
3.3. Accuracy and performance determination
For both induction-model and empirical approaches, correlation plots were calculated and compared with the measured $u_{2.5}$ equivalents, sometimes using conventional meteorological mast or ground lidar references at 2.5 D when they were available. The comparison results were summarised in terms of correlation gradients ($m$) and coefficients of determination ($R^2$).

4. Results

4.1. 1 D induction model

4.1.1. Example 1: flat terrain, central Germany
A ZX Lidars ZX TM was mounted on the nacelle of a 3 MW turbine, with a rotor diameter ($D$) of 116 m, and a hub height (HH) of 135 m. The ZX TM is a continuous-wave, circular scanning lidar, optimised for turbine nacelle deployment and capable of detailed wind field measurements over the entire rotor area. Lidar measurement ranges were set to be 0.75 $\zeta$, 1.0 $\zeta$, 1.3 $\zeta$, 1.59 $\zeta$, 4.9 $\zeta$ and 6.0 $\zeta$. The 10 minute averaged HH wind speeds from the shortest 4 of those ranges were used to perform the fit to the Medici model. In addition to the standard lidar quality and turbine operational filters, acceptance filtering for a 60° sector was performed.

Figure 3 shows some results for the campaign that ran for a period of 3 months. On the left is shown a single 10 minute wind speed result. The measurements made by the lidar are shown as points, and the Medici model least-squares fit of the 4 inner ranges is shown by the curve. In the example shown, the determined induction factor $\alpha$ of 0.441. Good agreement of the fitted model and the measured wind speeds is evident. On the right, a correlation plot is shown, comparing the lidar measured 6.0 $\zeta$ wind speed with that of the model-determined 6.0 $\zeta$ value.

![Figure 3](image.png)

Figure 3. Left: a single 10 minute example period showing the measured lidar wind speeds and the fit of the 1 D induction zone model to the closest 4 ranges to the rotor. Right: Correlation result comparing lidar-measured 3 D (6.0 $\zeta$) HH windspeeds with the 3 D results determined from the model.

4.1.2. Example 2: Complex terrain, Scotland
The previous example discussed a site in simple terrain. One of the claimed benefits of measuring wind speeds inside the induction zone is that it should reduce measurement uncertainty in complex terrain.
To help test this, the results in this section were drawn from a sophisticated measurement campaign performed concurrently on a windfarm in Scotland. 12 of the 25 turbines on the site were instrumented with ZX Lidars. The site is complex due to both terrain and the presence of forestry (figure 4). T20 was a 2 MW turbine, with HH of 68.5 m, and D of 92 m. Lidar measurements were made at ranges of 0.5 $\zeta$, 1.1 $\zeta$, 2.2 $\zeta$, 3.3 $\zeta$, and 5.0 $\zeta$. Lidar data filtering was performed as previously described, and the induction model fitting was made using the first 4 of those ranges. Correlations were made between the measured wind speeds at 2.5 D (i.e. 5 $\zeta$) and those wind speeds predicted with the model at the same range. Again, excellent agreement was obtained.

Figure 4. Left: T20 turbine location. The map’s elevation contour spacing is 10 m. The closest turbine spacing is approximately 360 m. Right: Correlation result comparing lidar-measured 2.5 D (5.0 $\zeta$) HH windspeeds with the 2.5 D results determined from the model.

4.2. Empirical transfer function approach

4.2.1. Example 1: flat terrain, Jutland

In this example ZX Lidars ZX TM was mounted on the nacelle of a 4.2 MW turbine, with a rotor diameter ($D$) of 150 m, and a hub height (HH) of 137 m. Measurement ranges were set to be 0.77 $\zeta$, 1.2 $\zeta$, 1.6 $\zeta$, 1.9 $\zeta$, 2.3 $\zeta$, 3.9 $\zeta$ and 5.0 $\zeta$. The ranges of 0.77 $\zeta$ and 3.9 $\zeta$ were chosen for the comparison. Apart from the standard lidar quality and turbine operational filters, no sector filtering was used, as the lidar’s flow complexity filtering made that unnecessary. The terrain was flat with some forestry.

The 4 months of campaign data was split into two parts. The first 2 months of data were used to calculate the transfer function, relating the hub height horizontal wind speeds at a range of 0.77 $\zeta$ (0.38 D) to 3.9 $\zeta$ (1.95 D). A least squares fit of a polynomial was used to determine this. The resulting transfer function and the data used is shown in the left of figure 5. The transfer function was then used to calculate the predicted 1.95 D data from the 0.38 D lidar wind speeds, and correlated with the measured lidar 1.95 D wind speeds. The result is shown to the right of figure 5.
4.2.2. Example 2: flat terrain, Germany

In this final example, the campaign described in section 4.1.1 was reanalysed, with the transfer function approach being used instead of the 1 D induction model. As before, the campaign was split into two parts. The first half was used to calculate the polynomial transfer function relating the lidar measured hub height windspeeds at 0.75 $\zeta$ range to those at a range of 6.0 $\zeta$. The second half of the campaign data was then used to investigate the effectiveness of the transfer function. The correlation results are shown in figure 6.

Figure 5. Left: the transfer function (red curve) between the lidar measured wind speeds (blue points) at 0.38 D and 1.95 D ranges using the first 2 months of data. Right: The last 2 months data of the campaign were used to correlate the measured 1.95 D wind speeds with those calculated using the measured 0.38 D lidar wind speeds multiplied by the transfer function.

Figure 6. Campaign in Germany. Left: the transfer function (red curve) between the lidar measured wind speeds (blue points) at 0.5 D and 3.0 D ranges using the first half of the data. Right: The last half
of the data of the campaign was used to correlate the measured 3.0 D wind speeds with those calculated using the 0.5 D lidar wind speeds multiplied by the transfer function.

5. Discussion
With gradients close to unity, and high values of $R^2$, good correlations were found when comparing propagated wind speed induction zone lidar measurements to measured wind speeds at longer ranges. These induction model and empirical approaches yielded good results for a variety of turbines and terrains. In general, the results using the induction zone model achieved slightly more accurate correlation results. This is likely to be due to that approach using wind speed information from multiple ranges within the induction zone, rather than the single range used by the transfer function method. This should naturally lead to reduced measurement uncertainties.

Unlike the induction model method, the transfer function method can be regarded as a calibration of a turbine’s induction characteristics. For identical turbine models, this might be required to be done only once, and the induction transfer function could be applied to whole wind farms of the same turbine model. Presumably scanning at a radius matching the rotor’s maximum spanwise power coefficient would be beneficial. Some of the analysis developed for optimizing lidar assisted turbine control configurations could be relevant [e.g. 9]. It is not clear how the transfer function would change with turbine ageing (for example, blade erosion), atmospheric effects or turbine control firmware upgrades.

For the induction model method, more sophisticated methodologies e.g. using two dimensional induction zone models [10], might yield reductions in uncertainty. It will also be important to extend analyses and methodologies to consider other relevant wind field quantities e.g. rotor equivalent wind speeds, TI (turbulence intensity), shear and veer profiles.

Importantly, the induction effect at these ranges is relatively small; e.g. even at 0.5D it has typically ~10% effect on wind speed. Hence, any error in the transfer function or induction model will translate to a much smaller uncertainty in the overall freestream calculation. Whilst further studies are being planned [e.g. 11] and industry is developing appropriate tools [12], it is hoped that the results presented in this paper will add confidence and impetus to future industry acceptance of these scalable and robust approaches to measuring free stream wind speeds of operating wind turbines.

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