Demonstration of short-range wind lidar in a high-performance wind tunnel

Authors: Anders Tegtmeier Pedersen[1,*], Belen Fernández Montes[2], Jens Engholm Pedersen[3], Michael Harris[4] and Torben Mikkelsen[5]
[1]DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark
[2]LM Wind Power
[3]NKT Photonics A/S
[4]ZephIR Ltd., Natural Power, The Old Barns, Fairoaks Farm, Hollybush, Nr Ledbury HR8 1EU, U.K.
[5]DTU Wind Energy, Technical University of Denmark

Summary

A short-range continuous-wave coherent laser radar (lidar) has been tested in a high-performance wind tunnel for possible use as a standard component in wind tunnels. The lidar was tested in a low as well as a high speed regime ranging from 5-35 m/s and 40-75 m/s, respectively. In both low and high-speed regimes very good correlation with reference measurements was found. Furthermore different staring directions were tested and taking a simple geometrical correction into account very good correlation was again found. These measurements all demonstrate the high accuracy of the lidar and indicate a possible future for short range lidars as a complement to LDA and other standard equipment in wind tunnels.

Introduction

The use of wind lidars for e.g. wind farm site assessment has increased in the recent years as a logical consequence of improvement in accuracy and reliability. Lidars are also emerging as a tool for active turbine control [1,2,3]. Some of the advantages of lidars for wind speed measurements lie in the fact that they measure remotely, meaning that no tall mast is necessary, and that they can easily be moved from site to site. This not only applies for atmospheric measurements, but could also be utilized in e.g. wind tunnels where one would benefit from a spatially localised measurement at almost any point in space without disturbing the flow. However, there have been few, if any, studies reported in which the technique of coherent laser radar has been applied in a wind tunnel environment.

In this study we test a short-range continuous-wave (CW) lidar for use in a high-performance wind tunnel and compare its performance against a calibrated pitot tube as well as a system of pressure sensors and extremely good correlation is found. Notably, the high sensitivity of the lidar allowed measurements to be carried out without any additional seeding of the tunnel; the ambient scattering level, even in the very clean air of the tunnel, was sufficient for the experiments reported here.

Experimental setup

The lidar used in these tests is CW Doppler lidar model ZephIR 300 from Natural Power [4], but with certain modifications regarding the transceiver unit. The transceiver unit is a telescope with a 2 inch diameter lens, manually adjustable focus and staring beam i.e. the beam is not scanning. The telescope is connected to the lidar base unit only through a 35 m fibre optical duplex cable led through a hole in the tunnel wall meaning that the base unit can be placed outside the wind tunnel during operation. The focus length of the telescope can be set from 1 m to 20 m and this short focus is necessary due to the tight confinements of the tunnel. For comparison two reference systems are used; one is a pitot tube placed in the middle of the

---

[*] Corresponding author. Address: Ørsteds Plads 343, 2800 Kgs. Lyngby, DK-Denmark, e-mail: antp@fotonik.dtu.dk, Tel.: +45 45256352, Fax: +45 45936581

tunnel test section and the second is a system of pressure sensors situated along the walls of the tunnel. The transceiver is placed inside the wind tunnel on a crossbar pointing into the flow of the wind but can be rotated around the crossbar e.g. for test of different angles-of-attack.

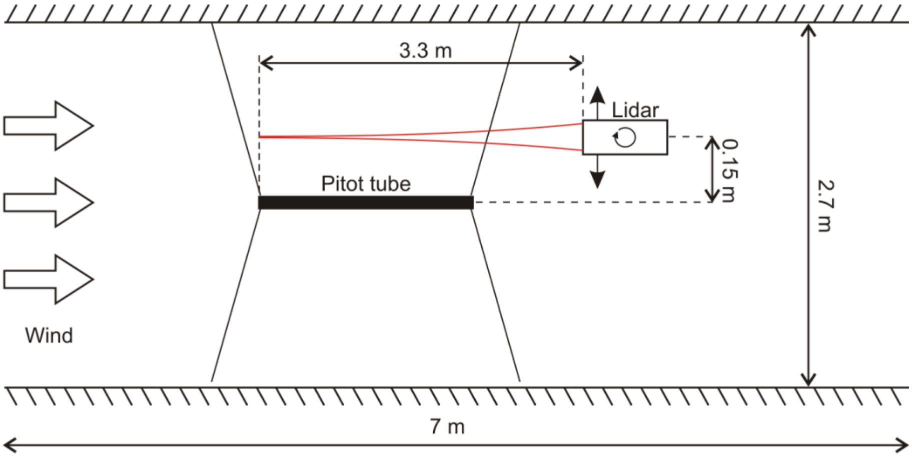

Figure 1 Sketch of the experimental setup. The lidar is mounted on a crossbar and points into the wind. The lidar can be rotated for test of different angle-of-attacks.

Figure 2 Photograph taken during the experiments showing two lidar transceivers mounted inside the wind tunnel.

Results

Different measurements have been carried out testing the lidar over a wide range of wind speeds and in different staring angles compared to the flow (angle-of-attack). These measurements are presented in the following sections.

Low speed regime

In the first series of tests the wind tunnel was ramped up in steps with stable wind speeds while measuring this speed using the lidar, pitot tube and pressure sensor systems. The lidar was accurately aligned to stare horizontally into the flow. The focus distance of the laser beam was set to 3.3 m resulting in a probe length of approximately 11 cm, defined as the distance separating the points either side of the focus, at which the sensitivity has dropped to 50%.The waist of the beam, representing the centre of the probe length, was placed well inside the stable test section of the tunnel just a few centimetres above the reference pitot tube as shown in Figure 1. Each step when ramping up the wind speed in principle lasted 7 minutes, but due to the time it took to stabilize the wind speed at the pre-set value only data representing the last 2 minutes of each step was used for further analysis. In the first test series the speed was increased from 5 m/s to 35 m/s in steps of 5 m/s. In Figure 3 is shown an example of these measurements. All three measurement systems show good agreement on the average wind speed for every step, but it is clearly seen that the pitot tube measurements are much less stable for low wind speeds than the pressure sensor and lidar measurements. Figure 4 shows the mean wind speed over 2 minutes for each pre-set speed measured by the lidar and plotted against the mean speed recorded by the reference pitot tube in the same time intervals. Shown is also a linear fit to the data points (note that the fit has been forced through the point (0,0)). As seen a very good correlation between the two measurements is found with a slope of the fit of 1.0084 and a coefficient of determination (R-value) of 0.99994, and equally good correlation was found when comparing the lidar measurements with the other reference system the pressure sensors. The lidar thus demonstrates the capability of operating in a wind tunnel at these speeds.

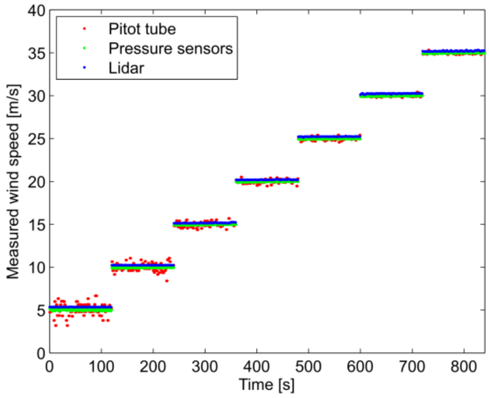

Figure 3 Wind speeds measured by the pitot tube, pressure sensors, and lidar, respectively. Each step represents 2 minutes of data.

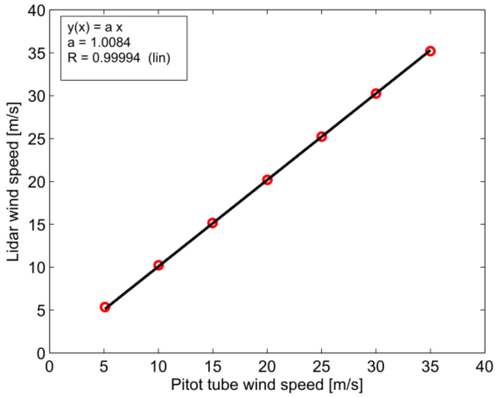

Figure 4 Plot of the mean wind speeds measured by the lidar against the wind speeds measured by the reference pitot tube. Excellent correlation between the measurements is observed.

High speed regime

In the second test series the wind speed was stepped from 40 m/s to 75 m/s in steps of 10 m/s except for the last step of only 5 m/s. The telescope was unaltered and data was processed in the same manner as in the test above and as can be seen in Figure 5 equally good correlation was found between the lidar measurements and the pitot tube with a slope of 1.0035 and R-value 0.99999. Based on these measurements it is clear that the lidar demonstrates full capability to measure high wind speeds up to 75 m/s and performs just as well in this range as in the low speed regime.

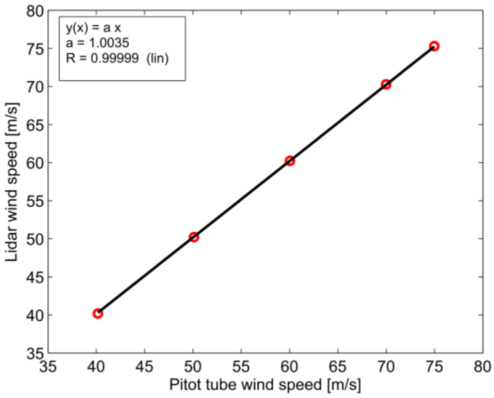

Figure 5 Plot of the mean wind speeds measured by the lidar against the wind speeds measured by the reference pitot tube.

High angle-of-attack

In a practical application it might not be very convenient to have the telescope mounted in the middle of the wind tunnel. In many situations it would instead be advantageous to have the telescope mounted at or near the tunnel wall minimizing the disturbance of the flow. The crossbar was therefore raised to the top of the tunnel and the telescope rotated so that it pointed downward in an angle of 66.5 compared to the flow. This results in a reduction in the wind speed measured by the lidar through the simple relation

$$\frac{\quad}{\quad} \qquad (1)$$

where is the speed in the direction of the flow, is the speed measured by the lidar and is the angle between the flow and the laser beam and in this case 66.5 . In order to keep the probe volume in the centre of the wind tunnel the focus length was reduced to 1.05 m resulting in a beam waist radius of only 52 µm and a probe length of 1.1 cm. Such a small probe volume can affect the statistics of the received backscatter signal [5]. The speed was increased from 10 m/s to 70 m/s in steps of 10 m/s and Figure **6** shows the resulting correlation plot after correction of the lidar speed according to Eq. (1) and with the pitot tube as reference. Once again a very good correlation is seen with an R-value closely approaching unity despite the very small probe volume. It should be noted that it seems the lidar measures a slightly lower wind speed than the pitot tube. However, this could very well be explained by a small inaccuracy in the measured angle θ, or a slightly inhomogenous flow pattern within the tunnel.

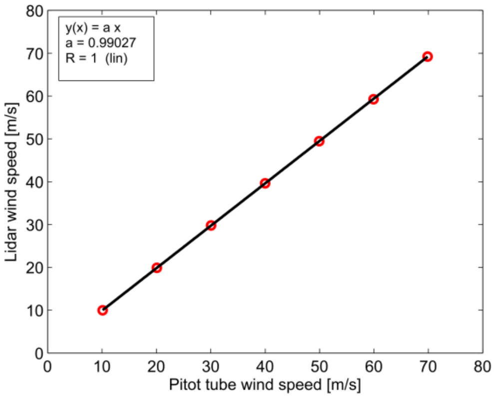

Figure 6 Plot of the mean wind speeds measured by the lidar after correction according to Eq. (1) against the wind speeds measured by the reference pitot tube.

Conclusion

A CW wind lidar, originally designed for atmospheric wind-speed measurements for the wind industry, has been modified and has demonstrated successful operation within an unseeded wind tunnel. As far as we are aware, this is the first such demonstration to be carried out. The technique is shown to have potential for non-intrusive flow investigation at high data rates, and thus could complement existing wind tunnel diagnostic methods.

Only the transceiver unit is physically located inside the tunnel but is connected to the base unit through an optical cable making it easy to move around for testing of different locations. Wind speeds ranging from 5 m/s to 75 m/s have been measured and these compare very highly against the tunnel's calibrated sensor systems across the entire range, providing further confidence in the long-term calibration of lidar for resource assessment, or for e.g. enhanced turbine pitch control via small telescopes integrated into the blades. Due to the absolute nature of the lidar measurement, no calibration of lidar speed was required either before or during the tests. In addition, the high stability and accuracy of lidar calibration suggests a possible use for cross-calibration of different wind tunnels, as well as potential for lidar to supersede cup anemometry as a primary standard.

Other experiments were performed, including investigations at different range settings and angles to the flow. Turbulence studies were also undertaken, and in a subsequent trial, a dual-telescope arrangement was successfully employed to characterise the flow in 2D. Analysis of these tests is ongoing and the results will be reported at a later date.

Acknowledgements

The work has been funded by Danish Advanced Technology Foundation:
Grant 049-2009-3: Integration of Wind LIDAR's In Wind Turbines for Improved Productivity and Control.
Steen Andreasen, IPU; Lyngby, Denmark is gratefully acknowledged for his skilled mechanical concept and mechanical design of the lidar telescopes.

References

1. Harris M, Bryce D, Coffey A, Smith D, Birkemeyer J, Knopf U. Advance measurements of gusts by laser anemometry. *Journal of Wind Engineering and Industrial Aerodynamics* 2007; 95:1637-1647
2. Mikkelsen T, Hansen KH, Angelou N, Sjöholm M, M Harris, Hadley P, Scullion R, Ellis G, Vives G. Lidar wind speed measurements from a rotating spinner. *EWEC 2010 online Proceedings 2010*
3. http://www.windscanner.dk
4. http://www.yourwindlidar.com
5. Harris M, Pearson GN, Ridley KD, Karlsson CJ, Olsson FÅA, Letalick D. Single-particle laser Doppler anemometry at 1.55 µm. *Applied Optics* 2001; 40:969-973