Lidars for Wind Tunnels - an IRPWind Joint Experiment Project

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Abstract

Measurement campaigns with continuous-wave Doppler Lidars (Light detection and ranging) developed at DTU Wind Energy in Denmark were performed in two very different wind tunnels. Firstly, a measurement campaign in a small icing wind tunnel chamber at VTT in Finland was performed with high frequency measurements for increasing the understanding of the effect of in-cloud icing conditions on Lidar signal dynamics. Secondly, a measurement campaign in the relatively large boundary-layer wind tunnel at NTNU in Norway was performed in the wake of a scaled test turbine in the same configuration as previously used in blind test comparisons for wind turbine wake modelers. These Lidar measurement activities constitute the Joint Experiment Project "L4WT - Lidars for Wind Tunnels, with applications to wakes and atmospheric icing in a prospective Nordic Network" with the aim of gaining and sharing knowledge about possibilities and limitations with lidar instrumentation in wind tunnels, which was funded by the IRPWind project within the community of the European Energy Research Alliance (EERA) Joint Programme on Wind Energy.

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1. Introduction

Lidars for Wind Tunnels (L4WT) is a project that has emerged from the cross-fertilization of mainly four different research creations.

Firstly, a scanning continuous-wave (cw) Lidar, the short-range WindScanner, has been developed at DTU Wind Energy over the last decade primarily for applications on full-scale wind turbines [1] although it has found applications also within aviation [2], micrometeorology [3], and wind engineering [4] etc. Furthermore, a compact Lidar

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telescope (Lidic) has been developed for close-range measurements from the moving blade of a wind turbine [5].

Secondly, wind tunnels are often only equipped with point monitoring in-situ devices such as hot-wire probes or pitot tubes that need large frames disturbing the flow under observation in order to obtain spatially resolved measurements of the flow fields. Alternative optical approaches commonly used in wind tunnels such as Laser Doppler Velocimetry (LDV) or Particle Image Velocimetry (PIV) have limited range and are not appropriate for measuring over larger spatial scales. In this context, the idea of using wind Lidars with scanning possibilities has recently emerged [6] as an alternative to close the spatial gap needed in larger wind tunnels.

Thirdly, icing conditions are causing substantial problems within the wind energy industry in the form of deteriorated blade aerodynamics, ice throw, increased noise, and limited access for repairs etc. In this context, ideas about using Doppler Lidars for detection of in-cloud icing conditions have emerged from observations of variations of the range dependent attenuation profile of pulsed Doppler Lidars depending on the icing conditions present [7].

Fourthly, an integrated research programme called IRPWind is on the European research scene. It combines strategic research projects and supports activities within the field of wind energy, with the aim of leveraging the long term European research potential. IRPWind integrates capacities and resources around the development of high risk technologies, allowing Europe to maintain its global competitive leading position in terms of research excellence and implementation of wind power technologies. IRPWind provides a European added value by promoting joint collaborative projects and overall reinforcement of research excellence within the wind energy sector, which will be of key importance to the sustainability and economic growth of Europe.[8]

The Joint Experiment Project "L4WT - Lidars for Wind Tunnels with applications to wakes and atmospheric icing in a prospective Nordic Network" is funded by the IRPWind project within the community of the European Energy Research Alliance (EERA) Joint Programme on Wind Energy. Based on the aim of the IRPWind, which is to foster better integration of European research activities in the field of wind energy research with the aim of accelerating the transition towards a low-carbon economy and maintain and increase European competitiveness, the L4WT project brings together boundary-layer wind tunnel and scaled wind turbine testing expertise from NTNU and SINTEF in Norway and cold climate and icing wind tunnel expertise from VTT in Finland with wind Lidar expertise from DTU in Denmark with the aim to gain and share knowledge about the possibilities and limitations with Lidar instrumentation in wind tunnels and to foster collaboration for alignment of research activities relevant to Lidars in wind tunnels and wind conditions in cold climate.

2. The Lidar instruments

The scanning cw lidar called the short-range WindScanner [9], which has been developed at The Technical University of Denmark (DTU) for applications on full-scale wind turbines achieves its range resolution by focusing the laser beam. Since the sampling volume scales quadratically with the measurement range, it is 100 times smaller at 10 meters range than at 100 meters range. Thus, the sampling volume is only about 0.1 meter long at 10 meters measurement range and relevant for wind tunnel length scales. However, the available length of the translational stage for the optical fiber tip relative to the focusing lens limits the focus range to beyond about 8 meters in the current implementation. The particular units used had the minimum range of 7.74 m and 8.02 m for R2D1 and R2D2, respectively. However, compact Lidar telescopes (Lidics) has also been developed and the advantage in addition to the compactness is the ability to focus the laser beam at very short sub meter distances. However, the beam aperture diameter is smaller on the Lidic than on a short-range WindScanner, which makes the probe volume of a Lidic larger than of a short-range WindScanner at a given measurement range.

In the experiments performed within this project, the Lidic has been focused at a distance of 1.5 m and in Fig. 1 the dimensions of the probe volume based on optical beam profiling measurements are provided. The minimum waist diameter is seen to be about 0.2 mm wide and the corresponding intensity profile along the beam, i.e., the Lorentzian-
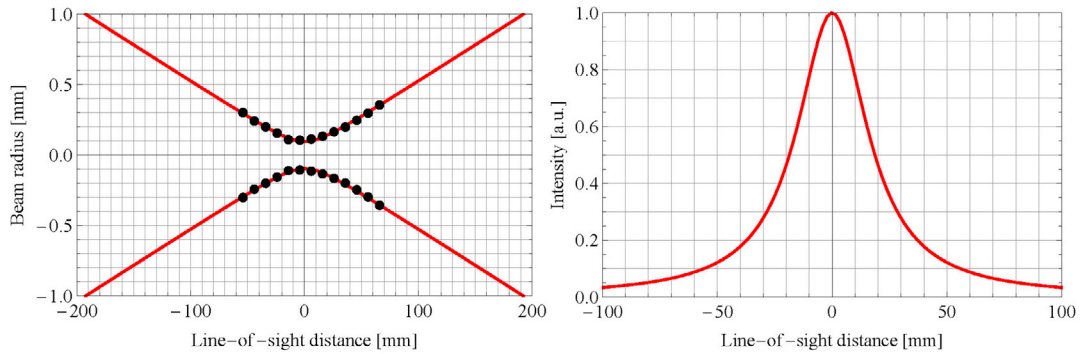
Fig. 1. (Left) The lateral beam radius of the Lidar Lidic telescope when focused at a distance of 1.5 m. The dots are based on measurements by an optical beam profiler and the minimum waist diameter is seen to be about 0.2 mm wide. (Right) The corresponding intensity profile along the beam normalized by the peak value, i.e., the Lorentzian-shaped sampling profile, can be seen to have a full width at half maximum (FWHM) of less than 40 mm.

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3. The icing wind tunnel experiment

Fig. 2. (Left) The Lidar telecope (Lidic) on a robotic arm in the icing wind tunnel. (Right) Lidic with an ice prevention system that keeps the optical window free from ice and water.

VTT in Espoo in Finland has a small icing wind tunnel (IWT) chamber research infrastructure which can create variable in-cloud icing conditions by varying wind speed, temperature, droplet size, and water amount. The Icing Wind Tunnel has a quadratic cross section of 0.7 m and is located inside a climate chamber which allows the in-cloud icing conditions into the test section. The temperature can be controlled in the range between -20 °C and +25 °C and wind speeds up to 50 m/s can be produced with water content between about 0.1 and 1 g/m^3 and the droplet sizes can be controlled within the range between 17 and 35 μm. The typical reference case for wind turbine rotor blades has a temperature of -5 °C and a wind speed of 40 m/s using a water content of 0.2 g/m^3 and a mean droplet size of 20 μm [10].
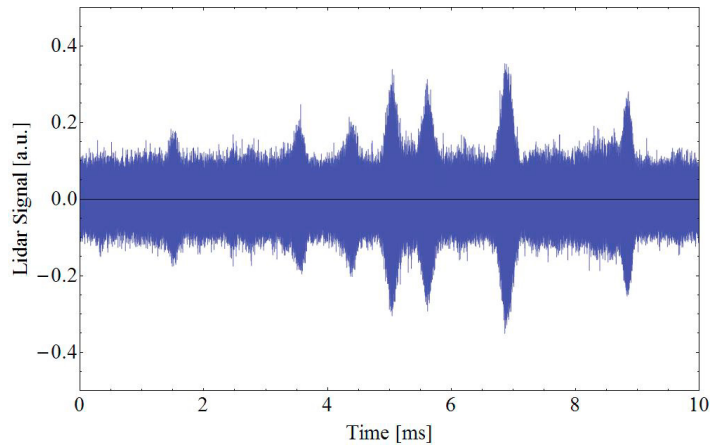
Fig. 3. A typical Lidar signal time series sampled at 120 MHz along the wind direction with bursts from water droplets. The signal is given in the arbitrary voltage unit provided by the analog to digital converter and the external conditions here were -5 °C, 0.034 g/m^3 water content, 10 m/s and an average droplet size of 20 μm.
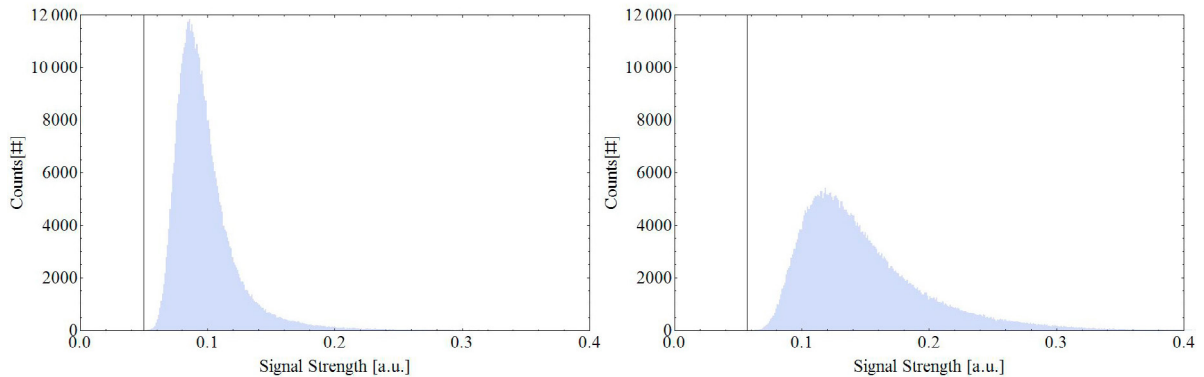

Fig. 4. The distribution of Lidar signal strengths taken as the maximum value of the coherent Lidar signal in each consecutive partition of 256 samples acquired at 120 MHz. The data presented are given in the arbitrary voltage unit provided by the analog to digital converter and the distributions are derived from one single measurement period of 1 second at a temperature of -5 °C, and a wind speed of 10 m/s for each of the cases (Left) 0.034 g/m^3 water content and (Right) 0.18 g/m^3.

One Lidar telescope (Lidic) mounted on a collaborative robotic arm, UR5 from Universal Robots, was used for the measurements as seen in Fig. 2. In order to protect the robotic arm from the harsh temperature and water conditions, it was wrapped with an electrical heating cable and surrounded by a flexible standard ventilation tube. The laser and the detection system was placed in a control room with standard room temperature conditions and connected to the telescope by optical fibres. In order for the passage of light from the telescope out to the measurement location 1.5 m in front of the telescope not to be hindered by water and ice cover, a small chamber was built and placed in front of the telescope window as seen in the right part of Fig. 2. The chamber was flushed with air of higher temperature, which worked fine for almost all conditions tested.

Due to the slow process of stabilizing the temperature in the icing wind tunnel, the test cases were run at only -5 °C and -15 °C. Various positions of the telescope and various angles relative to the flow direction were tested for a whole range of wind speeds and amounts of water. The water amount was simultaneously reference measured by the weight of ice accumulation on a standard rotating cylinder.

Raw Lidar signals sampled at 120 MHz were stored in 1 s long time series with a few seconds dead time during the storage process. With the small Lidar measurement volume the passage of individual droplets [11] can be observed

as seen in Fig. 3, where data from a typical Lidar time series along the wind direction at a temperature of -5 °C, and with a water content of 0.034 g/m^3 at 10 m/s with an average droplet size of 20 μm.

An example of the distribution of the Lidar signal strengths based on a total measurement period of 1 second at a temperature of -5 °C, and a wind speed of 10 m/s for a water content of 0.034 g/m^3 and 0.18 g/m^3, respectively is provided in Fig. 4. The fact that signal bursts can be seen in Fig. 3 indicates that the Lidar operates in the single-particle regime which is promising for further novel signal processing approaches. Although the details have to be investigated, the shift of the distributions towards larger Lidar signals for higher water content as seen in Fig. 4 indicates that there is potential for establishing quantitative relations.
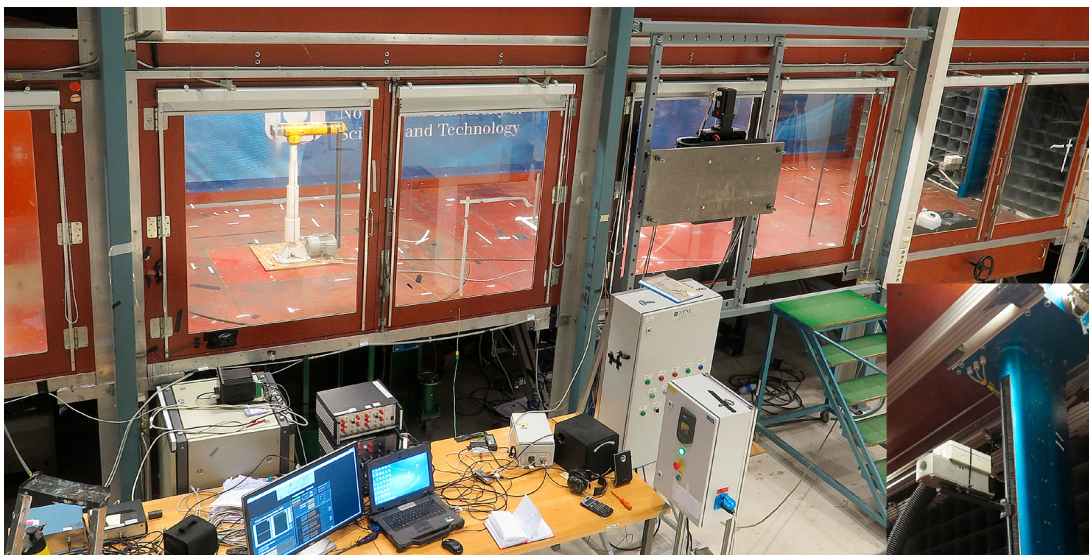
4. The boundary-layer wind tunnel experiment

Fig. 5. The experimental set-up in the boundary-layer wind tunnel at NTNU with the measurement plane located 5D downstream of the model wind turbine and the Lidic on a traversing system 1.5 m further downstream. In the insert a more detailed view of the Lidic on the traversing system can be seen.

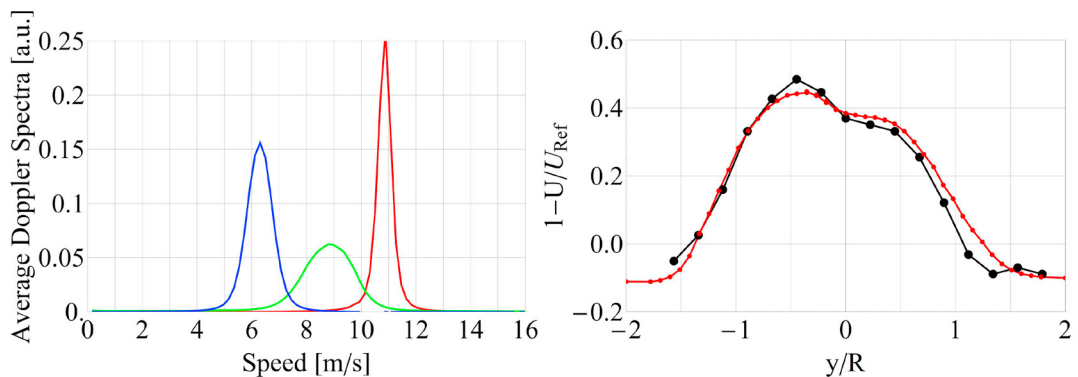

Fig. 6. Lidar measurements along the wind direction at 5D downstream of the model turbine running with a TSR of 6. (Left) The one minute median Doppler spectrum at the wake center (blue), 0.4 m to the side (green) and 0.6 m to the side outside of the wake (red). The spectra are normalized such that the integrals are all identical. (Right) The lateral profile of the velocity wake defect at hub height measured by the Lidar (black dots) compared with the historical blind test profile (red dots) [12].

NTNU in Trondheim in Norway has a boundary-layer wind tunnel [13] which has a test section that is 11 m long with a 1.8×2.7 m cross section and a 30 m/s max velocity. There are windows along one side of the tunnel as can be seen in Fig. 5 allowing for optical access from outside of the tunnel. This boundary-layer wind tunnel has previously been engaged in modeling comparisons on scaled wind turbines and in this experiment the very same turbine operated under the same conditions as in the blind test reported in [12] except for the location of the wind turbine which was located further downstream and slightly higher up than in the original blind test. The diameter of the model turbine used is 0.894 m and it is designed for a tip speed ratio (TSR) of 6.

As can be seen in Fig. 5, a small Lidar telescope (Lidic) was mounted on an existing traversing system inside the wind tunnel. In addition, two short-range WindScanners with a minimum focus distance of about 8 m were placed outside the tunnel with the optical heads at the turbine hub height measuring through the wind tunnel windows. The short-range WindScanners can locate the measurement location by synchronized steering of two prisms and a translational stage of the optical fibre tip relative to the focusing lens. The Lidic was connected to the WindScanner steering system allowing for synchronized measurements.

In Fig. 6 some initial results of the line-of-sight Lidar Lidic measurements along the wind direction at 5 rotor diameters downstream of the model turbine running with a TSR of 6 at the free stream velocity of 10 m/s as was used in the historical blind test [12]. Fig. 6 shows the lateral profile of the velocity wake defect at hub height measured by the Lidar (black dots) compared with the historical blind test profile (red dots). The small deviation between the present and the historical wake profile could be explained by a slightly different height of the measurement line relative to the center of the asymmetric wake which is expected to be similar to the in detail characterized scaled turbine wake presented in Fig. 5a in Ref. [14]. The Lidar results are based on the one-minute median spectra for fixed measurement positions and three examples of such spectra are also provided in the left part of Fig. 6, where the turbulent flow inside the wake is manifested by wider spectra compared to the less turbulent flow outside of the wake.

5. Conclusions

The practical knowledge about Lidar instrument integration in various types of wind tunnels has been advanced by this project and awareness among the IRPWind and EERA partners about the possibilities and limitations with wind Lidars in wind tunnels will be created. The initial analysis of the measurement results looks promising and the data will provide opportunities for increased understanding of the possibilities and limitations with Lidar measurements with high spatial and temporal resolution on scales relevant for wind tunnels.

Fundamental knowledge about the influence of rain and ice on the Lidar signals with future development prospects for novel Lidar signal processing schemes with the aim of providing information about atmospheric icing and other related conditions is anticipated and further explored by analysis of the data obtained.

The comparisons in the boundary-layer wind tunnel will open up for more detailed understanding of the spatial and temporal filtering of the Lidar-measured turbulence [15]. The next step is to analyze the various measurements from the Lidic as well as from the WindScanners obtained at 1D, 3D, and 5D downstream distances for various turbine tip speed ratios both for static and dynamic scanning scenarios. In parallel, procedures based on a rotating wheel with traceable perimeter speed are developed for establishing a traceable calibration of the Lidar instruments. This approach provides prospects for Doppler Lidar to be used as a reference for pitot tube and other in-situ anemometry.

Acknowledgements

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