Wind Field Measurement at an Offshore Site by using Scanning Doppler Lidar

スキャニングドプラーライダーによる洋上サイトでの風況計測

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1. Introduction

Measurement and collection of accurate wind data is important in a wide range of wind energy applications, including: wind resource evaluation for prospective wind farm site; optimization of a farm layout; operation and control of turbines etc. General practice in wind energy industry is to use instruments mounted at a single or multiple height on meteorological towers in order to collect wind data. However, due to structural and cost constraints, such towers are usually about 100 m in height, and thus, they cannot measure wind field across the rotor of utility-scale turbines with typical hub heights of 80 to 100 m and rotor diameters of 80 to 160 m. As a result, remote sensing techniques and in particular lidar technologies are getting increasingly popular in wind energy research due to their ability to measure wind speeds over large regions.

Application of lidar for the measurements of vertical velocity and turbulence profiles have achieved significant progress in the recent years[1]. Multiple studies have proposed the use of dual or triple lidar systems for accurate deduction of velocity components and turbulence statistics [2,3]. However, most works on the measurement and characterization of wind turbine wakes are either based on nacelle mounted lidars [4] or rely on the multiple lidar system [5].

The current work aims to evaluate the performance of scanning Doppler lidar in reconstruction of wind field at an offshore site and also propose a practical approach to characterize wind turbine wakes. The study differs from others, since it is based on a single lidar and is not mounted on the nacelle.

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2. Test site and measurement setup

The measurement data are collected from the Choshi offshore wind energy test facility located about 3.5 Km offshore Choshi city of Chiba prefecture (cf. Figure 1). The facility consists of a 2.4 MW wind turbine (MWT92/2.4) with a rotor diameter D = 92 m and a hub height $z_h = 80\,\text{m}$, and a meteorological tower located 285 m east from the turbine. The meteorological tower has a platform at the height of 15 m above the mean sea level. Two lidars, WindCube V1 and WindCube100S are mounted on this platform. Except for the validation purpose, the current study primarily uses WindCube100S which is capable of performing 3D

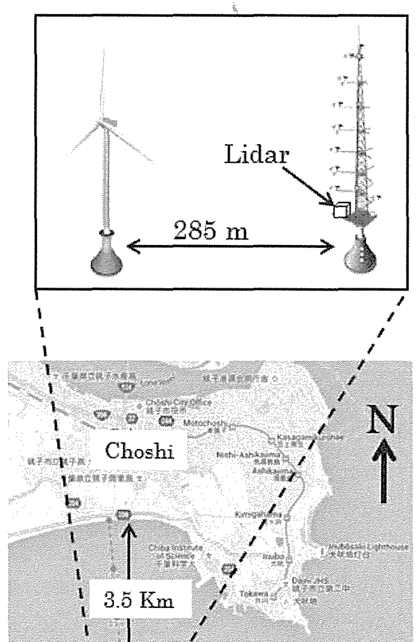

Figure 1. Google map of Choshi offshore site. The zoom in shows the location of wind turbine, observation tower and the scanning lidar.

volumetric scans. The meteorological tower has a height of 95 m, with three sonic anemometers located at z = 40, 60 and 80 m. In addition to that, several other sensors are mounted at eight different heights.

3. Measurement and validation of vertical wind profiles

In order to retrieve vertical profiles of wind speeds and directions, the line-of-site (LOS) wind speeds (u_r) is measured in Doppler Beam Swinging (DBS) scanning configuration. In this configuration the lidar beam is swung from north to east to south to west and to vertical directions. The wind speed can then be calculated at each measurement height using:

$$\mathrm{u} = \frac{u_{rE} - u_{rW}}{2\cos\phi},$$
$$\mathrm{v} = \frac{u_{rN} - u_{rS}}{2\cos\phi}, \qquad (1)$$
$$\mathrm{w} = u_{rV},$$

where u, v and w are wind speed components in west to east, north to south and vertical directions respectively. $u_{rE}, u_{rW}, u_{rN}, u_{rS}$ and u_{rV} radial wind speed along the LOS measured in east, west, north, south and vertical directions respectively. Finally, ϕ is the elevation angle and except for the vertical scan it is set to 62^0.

The measurements are first validated against the wind data retrieved using V1 lidar. Note that, wind speeds from V1 lidar were compared with the wind speed measured by high resolution sonic anemometer in an earlier study that showed good agreement between both techniques[6]. Figure 2 presents a comparison of the 10-minute averaged horizontal velocity and wind direction measured by 100S and V1 lidars at the height of 140 m. Except for some minor discrepancies there is a good agreement between both the measurements.

Figure 3 shows the vertical profiles for three velocity components and wind direction averaged over 12 hour time period. Once again, good agreement can be observed between the 100S and V1 measurements. Some differences observed in the comparison of v and w components can be attributed to their smaller magnitudes (less than 1 m/s). It is clear from the figure that 100S lidar is able to probe higher up in the atmosphere. Although range and quality of measurements depend strongly on the environmental conditions such as aerosol concentration, precipitation level etc, we found that the 100S lidar could usually measure up to 1200 m to 2000m height. This is higher than typical

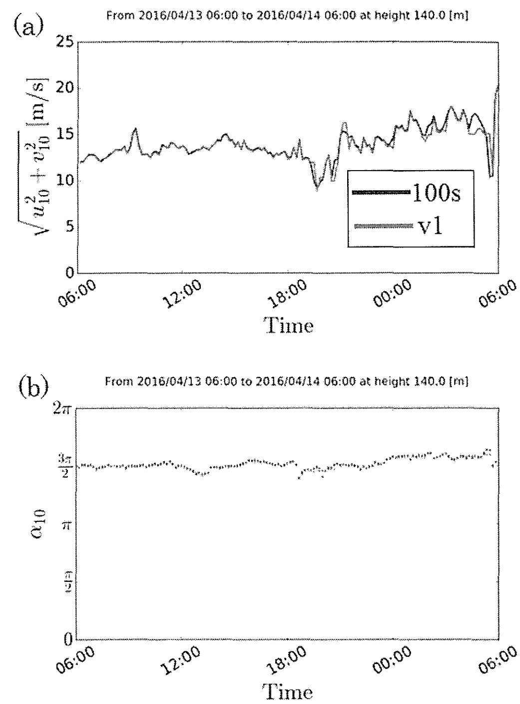

Figure 2. Comparison of the measurements of 100S with V1. (a) 10 minute-averaged horizontal velocity. (b) 10 minute-averaged wind direction.

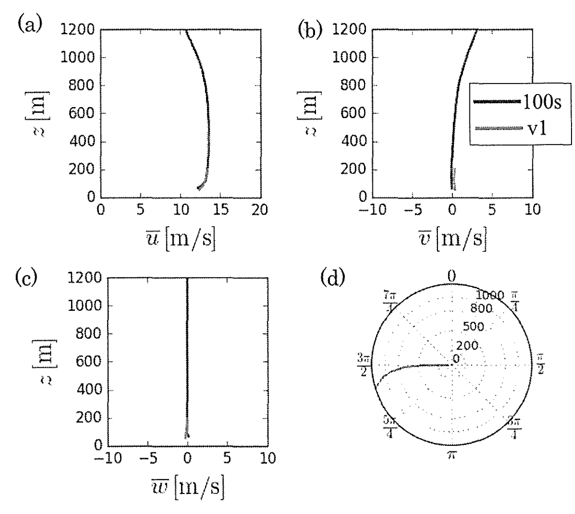

Figure 3. Vertical profiles of (a) west-east, (b) south-north, (c) vertical velocity components and (d) wind direction

atmospheric boundary layer (ABL) depth (300 m to 1000 m).

4. Flow reconstruction from 3D volumetric scan

In this section, we present a method for reconstruction of three-dimensional flow field from the lidar-measured radial wind speed and then apply the method to visualize wind turbine wake.

The lidar measurements are carried out in plan-position indicator (PPI) scan mode. In this mode, the lidar beam sweeps over a range of azimuth angle (θ), while maintaining elevation angle (ϕ) at a constant value. The step is repeated for the pre-defined set of elevation angles in order to generate 3D volumetric data. Figure 4 shows an example of a PPI scan at an elevation angle of $\phi = 13^{\circ}$. The region $\pi/2 \leq \theta \leq \pi$ has been excluded to avoid blockage due to meteorological tower and other installations on the platform.

4.1 Approach and validation

Without going into the mathematical details, radial velocity measured by a Doppler lidar can be expressed as the projection of the actual velocity vector in the laser beam direction (cf. Figure 5), i.e.

$$\begin{aligned} u_r &= \boldsymbol{V} \cdot \boldsymbol{a}_r \\ &= u \cos\phi \sin\theta + v \cos\phi \cos\theta . \quad (2) \end{aligned}$$

Here, **V** is the velocity vector, $\boldsymbol{a}_r$ is a unit vector along radial direction and we have neglected the vertical velocity component w as it is very small. Furthermore, u and v components can be written as

$$u = V \sin\alpha, \quad v = V \cos\alpha, \qquad (3)$$

with $V = \sqrt{u^2 + v^2}$ being the magnitude of horizontal velocity and α the wind direction. If we assume that wind direction at every point in a scan is same as that measured by anemometer on the nacelle or the meteorological tower, reconstruction of velocity **V** can be straightforward by substituting (3) into (2).

Figure 6 shows the comparison of one hour-averaged velocity magnitude reconstructed from the lidar measurement with that measured by nacelle-mounted anemometer. In order to obviate the effect of the turbine wake on the nacelle measurement, the comparison was made when the turbine was stopped. Result shows good agreement between two measurements, justifying the use of this approach for further analysis of lidar data.

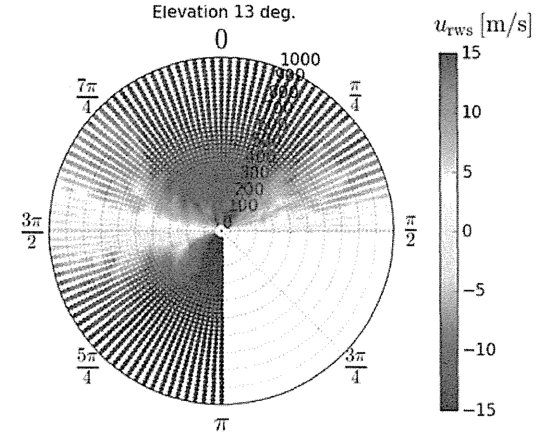

Figure 4. Radial wind speed measured using conical sector scan at an elevation angle of 13°.

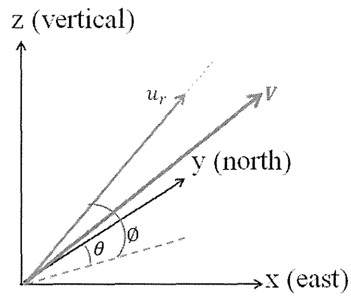

Figure 5. An arbitrary radial velocity u_r and correcponding velocity vector shown in the meteorological coordinate system.

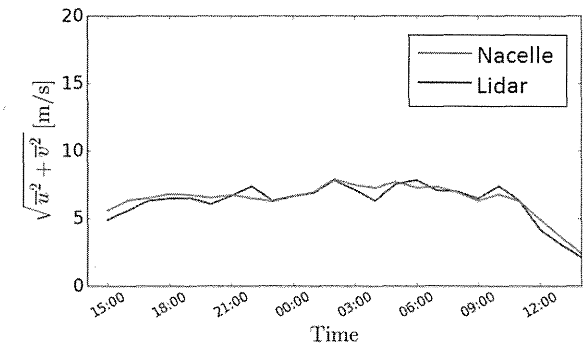

Figure 6. Comparison of velocity magnitude reconstructed from lidar measurement and the velocity magnitude obtained from nacelle-mounted anemometer.

4.2 Wind turbine wake visualization

The method discussed above is used to construct flow field in the wake of the wind turbine. Figure 7

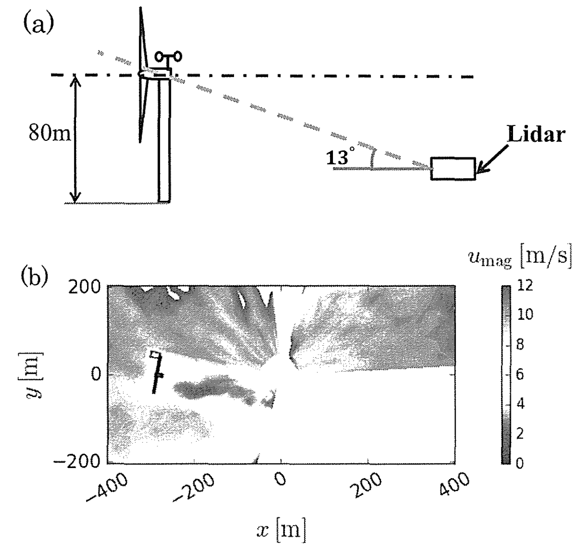

Figure7. (a) Schematic of a conical scan at an elevation angle of 13°. The lidar beam hit the nacelle at this angle. (b) Velocity magnitude of the conical plane at the elevation angle of 13°.

(b) shows the wake structure generated from a single elevation ($\phi = 13°$) sector scan. As depicted in Figure 7(a), the lidar beam passes through the hub height at this elevation angle. Similar to Figure 4, the bottom right quadrant has been excluded to avoid blockage due to installations on the platform. Additionally, we have also excluded data for which azimuth angles are approximately perpendicular to the incoming flow, because of high measurement error at these angles. Velocity deficit and meandering which are common characteristic of a turbine wake are clearly visible in the figure. The hub height velocity field (not shown here) constructed from multiple conical scans for the sequence of elevation angles showed significant velocity deficit in the wake until 6D to 7D downstream from the rotor position. This has also been observed in wind tunnel experiments and LES studies (see e.g. Wu and Porte-Agel [7]).

5. Summary

The current work validates the scanning Doppler lidar installed at the Choshi offshore wind energy research facility, and then demonstrates the capability of the lidar system for ABL measurement. The second part describes a method for reconstructing wind speed components from radial wind speeds measured by a lidar. It is based on the assumption that the wind direction is same at all the points in a scan. The method is then used to visualize wind turbine wake structure.

Future work will improve the method for characterization of flow field in the wake and also focus on the better scanning strategy which will allow for better data acquisition.

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