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Wake effect measurements on a complex-terrain wind field

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Abstract— The understanding of wind turbine wake interactions in large wind farms contributes to control power losses and turbulence increases, which is crucial to optimize the design of a wind farm. The wake effect in complex-terrain wind farms is much more complicated, and the related problems are still not investigated in depth. This study tries to fill in this research gap from the experimental aspect. This paper based on the wind field measurement in a typical complex-terrain wind farm in north China. The wind turbines are built in mountainous positions and the maximum height difference between wind turbines is 171.3m. A vertical-wind-mast-type lidar and a three-dimensional-scanning-wind lidar were used to measure wind turbine wakes. The multiple wake effect downstream of four aligned wind turbines are investigated. The numerical experimental data and results are demonstrated in this paper. Huge experimental difficulties exist in deciding proper lidar scan strategies and adopting effective integration of measured data from various remote sensing platforms. This study also summarizes the difficulties and gives out the experience from the measurements, which is a guidance for the future measurements in the complex-terrain wind farms.

Keywords—wind field experiments, complex-terrain, wake effect, a row of wind turbines.

I. INTRODUCTION

Wake effect is a complex phenomenon that is in connection to the wind turbine, the layout of wind farm and the characteristics of atmospheric. The wake spreads a long distance downstream of a wind turbine and returns to the surrounding wind gradually [1]. Huge difficulties also exist in deciding proper lidar scan strategies and adopting effective integration of measured data from various remote sensing platforms. Recently, the wake data from full scale experiment is particularly more needed in the wind energy industry. Advanced wind farm models based on comprehensive and accurate wake measurements are essential in the validation and development. In terms of optimizing the layout of wind farms, understanding of turbulence increase and power losses due to wake interactions is of great significance.

The history of measuring onshore wind farm wake effect is close to 40 years now. Early to the year of 1982, a field measurement was conducted at Goodnoe Hills, Washington, [2]. The objective was to determine the wind velocity deficit in centerline and its downwind development in different meteorological conditions. During 1992, a detailed measuring campaign was organized in the Sexbierum Wind Farm in Dutch [3]. The experiment aimed at collecting data on wind speed, turbulence intensity and shear stress in wakes at several downwind distances. The flat-terrain Nørrekær Enge wind farm [4] was used to validate the effectiveness of WindFarmer software in predicting the reduce in power production of the wake affected turbines in rows with varying spacings. MacHielse, et al. [5] collected the data from the ECN Wind turbine Test station Wieringermeer, which is situated in flat open farmland in the Netherlands. A series of CWEX experiments were conducted in the wind farm in central Iowa [6]. CWEX-10 and CWEX-11 experiments [6, 7] revealed the influence of one row wind turbines' on the local environment. CWEX-13 campaign demonstrated frequent nocturnal low-level jets and strong diurnal cycles of atmospheric stability [8]. The Risø test field is relatively located at a homogeneous terrain in Roskilde, Denmark. Based on the experiments from this wind farm, Bingöl, et al. [9] developed a measurement technique to directly measure the instantaneous wake effect. Then, Trujillo, et al. [10] dealt with the analysis of the two-dimensional wake measurements, which enabled to estimate the wind farm in sections perpendicular to the rotor axis. There were also some wake validation from remote sensing measurements, but only focused on individual isolated WTs rather than wind farms [11-16].

In recent years, significant progress has proved that it is complicated to extract robust and quantitative metrics of wake characteristics like length scale and velocity deficit [17]. In complex terrains, the issues of wake characterization are further enlarged [18]. On the one hand, it is challenging to describe the freestream with complex waves, turnings, and recirculation zones [19]; on the other hand, the wake behavior also has a close relation to the flow as well as the terrain slope [20, 21]. One of the first measurement of wind turbine wakes using lidar in the relatively complex terrain was involved in the Perdigão experiment [18]. The site of the wind farm is a double-ridge extending lasts several kilometers and the hilltop is 300 m higher than the local terrain [21]. Barthelmie, et al. [18] described wake measurements with lidars and investigated the advantages of data integration from various scanning strategies as well.

So far, the characteristics of wakes in complex terrains are still unveiled and not much wind field data could be used on this problem. Therefore, in the work described herein, we focus on the measurements in the complex-terrain wind fields. The site and layout of the tested wind farm are descripted in details. The measuring equipment, including the principle of lidars and two lidars applied in the experiments are introduced. Then the experimental data are analysed and discussed. Finally, summaries of this study are drawn.

II. SITE AND LAYOUT OF THE SHIREN WIND FARM

The experiment was conducted in the Shiren Wind Farm, which is located in Zhangjiakou City, Hebei Province, China. The terrain of the wind farm is characterized with low mountains and hilly areas. The largest difference of altitude in Shiren Wind Farm is 171.3 m. The highest one is installed at 1894.1 m high and the lowest one is installed at 1722.8 m high. This wind farm is a good representative of complex-terrain wind farm. The terrain of Shiren Wind Farm is demonstrated in Fig. 1 [22].

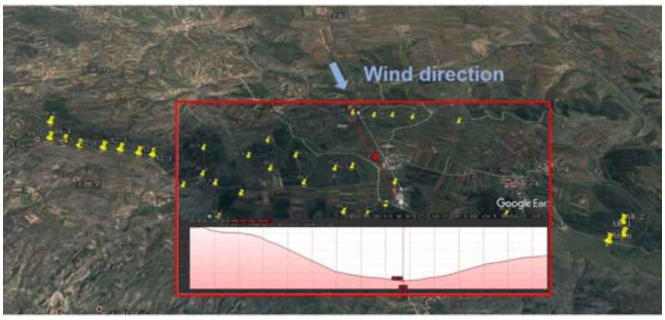


Fig. 1. Terrain of Shiren Wind Farm

Shiren Wind Farm has a capacity of 75MW. It consists of 50 1.5MW WTs, among which 33 are AW77-1500 and 17 are UP77-1500. For AW77-1500 WT, the rotor diameter is 77m and the hub height is 60m. For UP77-1500 WT, the rotor diameter is 77m and the hub height is 65m.

In this experiment, four wind turbines, WT10-1, WT10-2, WT10-3 and WT10-4 were selected to investigate the wake effect downstream of a row of wind turbines.

The first-hand wind speed data will contribute to either the research study or the engineering application in complex terrain wind farms.

III. MEASURING EQUIPMENT

In this experiment, two lidars have been used to obtain wind data. WindMast WP350 was applied to measure the inflow wind and Wind3D 6000 was applied to detect the downwind wakes. The schematic of wind lidar system is demonstrated in Fig. 2 [23].

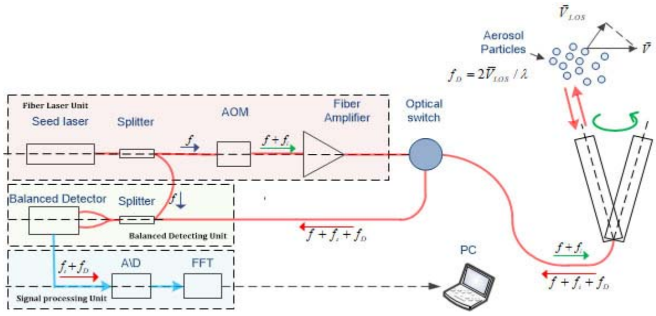


Fig. 2. Wind Lidar System Schematic

A. *Lidar measurement principle*

The atmospheric wind is the main driving force for atmospheric circulation, material transport and weather phenomena of various scales. Coherent wind lidar is a non-contact measurement, non-interfering target motion, high spatial and temporal resolution, high measurement accuracy and large range lidar system. It is an active remote sensing capable of measuring 3-D atmospheric wind field all day.

The coherent wind lidar system has three parts including a laser emitting system, an optical receiving system, and a signal acquisition processor. The launch system emits laser light into the atmosphere, interacts with the aerosol to generate an echo signal, which is received by the optical antenna, sent to the signal acquisition system for data process.

B. *WindMast WP350*

WindMast WP350 is a vertical-wind-mast-type lidar, which is designed to replace wind towers. It has a high precision, needs low power. The wind speed and wind profile of any 30 height gates from 20 m to 350 m above the lidar can be continuously detected throughout the day.

Fig. 3. WindMast WP350 before the target wind turbine (WindMast WP350 is circled by red line; WT10-2 is the target turbine and is circled by the yellow line)

C. *Wind3D 6000*

Wind3D 6000 is three-dimensional-scanning-wind lidar, which can realize the detection of 3-D wind fields of the middle and lower troposphere (including the atmospheric boundary layer). Wind3D 6000 has a high precision of optical scanning mirror for 3-D scanning. It also has several scanning modes and the detection radius can be up to 6 km. Wind3D6000 can meet the complex wind measurement requirements such as complex terrain wind field, wind turbine wake and remote virtual wind tower at sea.

Fig. 4. Wind3D 6000 and the target wind turbines (Wind3D 6000 is circled by red line; WT10-1, WT10-2, WT10-3 and WT10-4 are the target turbines and are circled by the yellow line)

Technical specifications of WindMast WP350 and Wind 3D6000 are demonstrated in TABLE I.

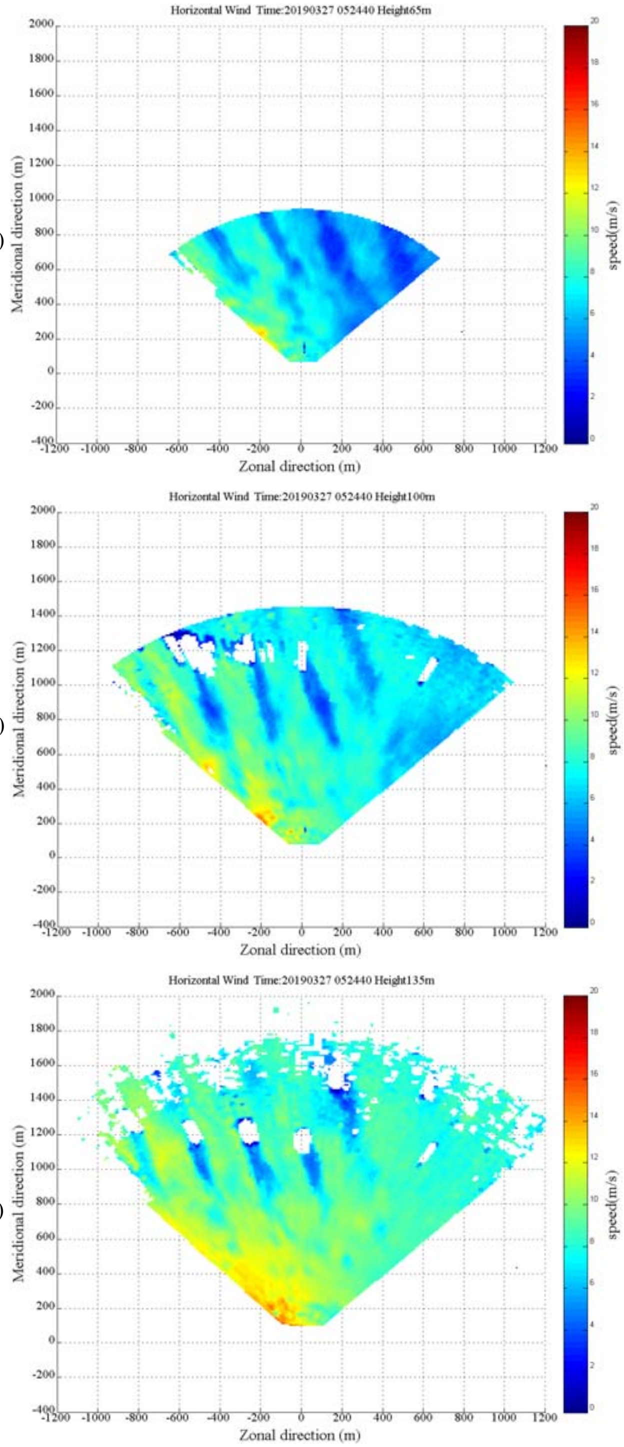
TABLE I. TECHNICAL SPECIFICATIONS OF WINDMAST WP350 AND WIND 3D6000

Specifications	**WP350**	**3D6000**
Wavelength	1.5 µm, eye-safe	1.5 µm, eye-safe
Detection height	20 m~350 m	45 m~6000 m
Spatial resolution	1 m (up to 30 heights in the range of 20~350 m)	15 m/30 m (configurable)
Data updating time/rate	1 s~10 min	1 Hz~10 Hz
Wind speed range	0~75 m/s	-37.5 m/s~37.5 m/s
Wind speed error	≤0.1 m/s	≤0.1 m/s
Wind direction error	<3°	±0.1°
Data product	Horizontal and vertical wind speeds, wind direction, mean square error of wind speed, wind shear index, SNR signal to noise ratio data, GNSS position time, radar status data, surface atmospheric temperature, humidity, pressure, etc.	DBS/VAD wind profile, vertical flow, RHI/PPI/CAPPI radial velocity, virtual tower stare, turbulence wake, wake vortex, wind shear, backscatter intensity, multi-lidar measurement, GNSS position, lidar status, temperature humidity, pressure
Weight	<30 kg	<90 kg

IV. RESULTS AND ANALYSIS

The effective results must be carefully selected from all measured data. They are supposed to be selected when four wind turbines were operating simultaneously, and no turbine was under the wake effect of other turbines. The stable wind should last long enough for lidars to measure the wind data, and the aerosol concentration must be within the operating ranges of lidars, which means the air could not be too dirty or too clean. PPI scanning mode was also applied in this experiment. A qualitied period is 3:27 am to 3:28 am, March 27th, 2019. The wind speeds and wind directions at the heights of 65 m, 100 m, 130 m and 170 m of the whole day are demonstrated in Fig. 3.

(a)
(b)
(c)



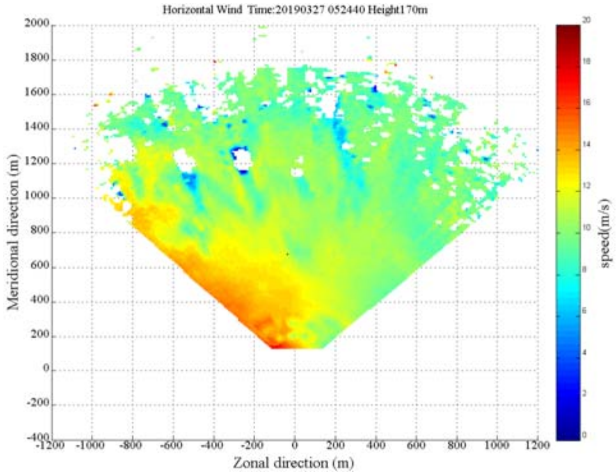
(d) 

Fig. 5. Measurements of wake effect at a series of heights: (a) at the height of 65 m; (b) at the height of 100 m; (c) at the height of 135 m and (d) at the height of 170 m.

From the measurements, the lidar can scan the 3-D wake distribution simultaneously. For the circular cone shape of the laser beam, the san scopes at different heights are not the same. In this experiments, the target is the horizontal plan of the hub height. Therefore, the scope at 135 m high is the largest, which decreases with the increase of the distance to the target plane and is the smallest at the height of 65 m.

The wake effect is significant in the near-wake zone. The width of the wakes can reach around 200 m and the length may be longer than 1000 m. There are some wake interactions long behind the turbines, which are related to the positions of turbines and directions of wind.

The incoming wind speed at the hub height is around 9 m/s, whereas the wind may decrease most to less than 2 m/s right behind the turbine. Comparing four sections, the environmental wind speeds are also different at all heights. The wind speeds in the high positions tend to be large than those in the low positions, which indicates that the wind variation should be involved in the consideration when estimate the wake effect.

Fluctuations were observed in the far-wake zone. The wakes are not quite asymmetrical to the centerlines and are not similar from one turbine to another. The range of the wake-influenced area was not easy to be identified, especially in the far-wake zone, where wakes of adjacent turbines had a complicated interaction.

V. Conclusions

In this paper, wind field experiments were carried out in order to analyze and better understand wake effect in the complex terrain. The work reported in this paper is summarized as follows:

Firstly, the site and layout of the tested wind farm were introduced. Shiren wind farm has a capacity of 75 MW and consists of 50 numbers of 1.5MW wind turbines of two types, which are installed at a complex hilly terrain in north China, where the wind resources are relatively rich. The largest difference of altitude is 171.3 m in the farm, with the highest altitude wind turbine installed at 1894.1 m high and the lowest altitude one installed at 1722.8 m. It is a good representative of a complex-terrain wind farm, of which the measured wind data deserves investigating in depth.

Two lidars were applied in the experiments. WindMast WP350 is a vertical-wind-mast-type lidar, which was used to measure the inflow before the wind turbine. Wind3D 6000 is three-dimensional-scanning-wind lidar. It was used to capture the wake development behind the tested wind turbines. Both the two lidars were calibrated by the anemometer tower in the wind farm first, and then were applied in the experiments.

One experiment was based on a row of four wind turbines. The effective results were selected when four wind turbines were operating simultaneously, and no turbine was under the wake effect of other turbines. From this experiment, huge deficits of wind speed in all four analyzing lines happen right behind the wind turbines. The wind speeds reduced most to around 2 m/s. The terrain in this experiment is much more complex, which has huge effect on the wake distribution in terms of deficits of wind speeds, centerlines and restoring wind speeds.

In conclusion, the experimental investigation presented in this study has provided a better understanding of the wind turbine wake characteristics. The complex terrain indeed makes the wake distribution more complicated, however, not much of the terrain factors have been involved in this study so far. Therefore, further study would be conducted focusing on how terrains influence the wake effect in the future.

Acknowledgment

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