J. Wind Eng. Ind. Aerodyn. 147 (2015) 164–175

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

# Intra-farm wind speed variability observed by nacelle anemometers in a large inland wind farm

Song-Lak Kang [a,*], Hoonill Won [b]

[a] Department of Geosciences, Texas Tech University, Lubbock, TX 79409-1053, USA
[b] National Wind Institute, Texas Tech University, Lubbock, TX 79409, USA

ARTICLE INFO

*Article history:*
Received 15 March 2015
Received in revised form
6 October 2015
Accepted 6 October 2015
Available online 28 October 2015

*Key words:*
Intra-farm variability
A large wind farm
Wind speed
Nacelle anemometer
Wind power production

ABSTRACT

Using 11-month, 15-min averaged measurements by nacelle anemometers at 274 wind turbines, we studied the spatial and temporal variability of wind speed in a wind farm over an area of about 20 km by 20 km located in mountainous terrain. The intra-farm variability is compared between winter and summer: during summer the dominant time scale of wind speed fluctuation is the diurnal cycle of 24 h. During winter, however, the dominant scale is 48 h. The spatial variability of wind speed on scales $\leq O$(10 km) is closely associated with the temporal variability on scales $\leq O$(10 h). Over a time span $\leq 3$ h rapid drop-offs in wind speed occur more often than rapid increases, and the rapid drop-offs are more frequent during summer than winter. The intra-farm spatial variability of wind speed has a diurnal cycle with that reaches its maximum in the nighttime and its minimum around midday. For accurate wind power modeling, it may be of importance to consider the intra-farm variability of wind speed distribution. We found that when energy production exceeds 200 MW, its estimation based on the averaged wind speed is significantly larger than when based on the speeds at individual turbines.



## 1. Introduction

A large onshore wind farm with a power capacity in the hundreds of megawatts (MW) usually occupies a local area of several hundreds of square kilometers. In such a large wind farm, inflow wind to each turbine may vary significantly (American Wind Energy Association, 2014; Denholm et al., 2009). In a region of similar size, in the absence of a wind farm, low-level atmospheric flows at the approximate height of a wind turbine hub are directly influenced by various mechanical and thermal characteristics of the earth's surface, like terrain height, roughness length, surface sensible and latent heat fluxes, and local circulations induced by their spatial heterogeneities. The effects of surface heterogeneities also vary depending on background weather conditions on scales larger than the local area. In a wind farm, wind flows may be extremely complicated by the co-occurrence of meteorological variations and turbine wake effects and their nonlinear interactions, particularly over strongly heterogeneous surfaces like coastal areas or mountainous regions. Considering that wind farms are often built over such heterogeneous surfaces, it is important to know the significance of the spatial variability of intra-farm wind flows as they influence power production. Wind power is positively proportional to the cube of wind speed in the range between the cut-in speed, about 3–5 m s$^{-1}$, and the rated wind speed, about 11–15 m s$^{-1}$ (Burton et al., 2011; Manwell et al., 2010; Poore and Lettenmaier, 2003; Wan et al., 2010). In places where wind resources are assessed as good or excellent, wind speed fluctuates mostly in this range (Wan et al., 2010). Thus, one can say that a small change in wind speed results in a large difference in wind power production. Actual measurements make it possible to investigate the spatial and temporal variations in intra-farm wind speed and interpret their impact on the accurate estimation of wind power.

Each turbine in a large wind farm is outfitted with an anemometer affixed to the turbine nacelle. Nacelle anemometer measurements of wind speed are used for verification and data assimilation for wind forecast modeling and for wind turbine controls. Intra-farm wind information is also obtained using instruments affixed to on-site meteorological (met) masts (Cutler et al., 2012; Manwell et al., 2010). Despite their common use in wind energy calculations, nacelle anemometer measurements have been criticized because the turbine rotor may distort the free-stream flow and so the measurement may be inaccurate in representing the inflow upon the rotor (Allik et al., 2014). Thus, met-mast measurements are often treated as more accurate for wind resource assessment and wind forecast evaluation. Since only one or two met-masts are usually installed in a large wind farm, however, met-mast observations are inadequate to measure the spatial variability

* Corresponding author.
*E-mail address:* song-lak.kang@ttu.edu (S.-L. Kang).

http://dx.doi.org/10.1016/j.jweia.2015.10.010
0167-6105/

of intra-farm wind (Cutler et al., 2012). Some studies suggest that nacelle anemometer measurements could be appropriate to capture inflow characteristics (Cutler et al., 2012; Smith et al., 2002; Wieringa, 1986), and their use has been growing (Beltran et al., 2013; Cutler et al., 2012; Landberg, 1999; Liu et al., 2011). On this basis we have conducted an investigation of intra-farm wind variations with nacelle anemometer measurements.

We studied the spatial and temporal characteristics of wind speed measurements by nacelle anemometers at 274 wind turbines in a large wind farm of an area of about 20 km by 20 km (Liu et al., 2011; Wan et al., 2010; Zhang et al., 2014). We analyzed 15-min averaged data of the nacelle anemometer measurements collected over the eleven months from 1 January to 30 November 2012. With this dataset, we tested the hypothesis that spatial variability of wind speed in a wind farm on scales $\le O(10\text{ km})$ is associated with temporal variability on scales $\le O(10\text{ h})$ (Manwell et al., 2010; Orlanski, 1975; Stull, 1988). We conclude by discussing the intra-farm spatial and temporal variability of wind speed in terms of the accuracy of wind power production estimates.

## 2. Data

Wind speed data used for this study were collected by 3-cup anemometers mounted on wind turbine nacelles in a wind farm of about $20 \times 20\text{ km}^2$ in northeastern Colorado (Fig. 1). The wind farm has 274 wind turbines (Liu et al., 2011; Wan et al., 2010; Zhang et al., 2014). The average distance between turbines in the same row is about 320 m, or roughly 5 rotor diameters. The distance among rows ranges from about 530 m to more than 8900 m (Wan et al., 2010; Zhang et al., 2014). Of the 274 wind turbines, the hub heights and rotor diameters of 221 wind turbines are 69 m and 62 m, respectively. The hub heights and rotor diameters of the others are 80 m and 77 m, respectively (Zhang et al., 2014). An anemometer is mounted on top of the nacelle housing of each turbine. The nacelle diameters are 3 m and 2.4 m, respectively, for the 80-m and 69-m hub-height wind turbines (GE Wind Energy LLC, 2006; Kuroiwa et al., 2004). For the 80-m (or 69-m) hub-height wind turbines, the distance of the nacelle anemometer from the rotor is about 3 (or 1.5) times the nacelle diameter, and the height of the anemometer above the nacelle is about 0.3 (or 0.3) times the nacelle diameter (Antoniou and Pedersen, 1997; GE Wind Energy LLC, 2006; Kuroiwa et al., 2004).

The nacelle anemometer data are 15-min averaged wind speeds at the 274 wind turbines from 1 January to 30 November 2012. From the same wind farm, the wind measurement data have also been used for some previous published studies (Liu et al., 2011; Wan et al., 2010; Zhang et al., 2014). In particular, the 15-min averaged data set we used for this study was provided from the investigators of Liu et al. (2011). Thus, we assume that the same quality control and averaging processes used for the observational data of Liu et al. (2011) has been applied for the provided dataset.

First, it is of importance to note that in the provided 11-month time series, 14% of the data points are missing, which made this study very challenging. Table 1 summarizes the percentage of missing data points and the median value of the longest periods of consecutive missing data points at all the 274 wind turbines for each month and for the total 11 months.

As shown in Fig. 1, this wind farm is located in a mountainous region. The mean and standard deviation of terrain heights over the area of 20 km by 20 km (Fig. 1a) in which all the 274 wind turbines are located are 1610 m and 50 m respectively. In Fig. 1b, the 30 arc second (about 900 m) terrain data from the NASA Shuttle Radar Topography Mission demonstrate the mesoscale terrain slope from the Rocky Mountain Front Range region in the northwest of the wind farm to the foothills in the southeast. Liu et al. (2011) exhibit their sub-km grid spacing simulation of a large area of down-slope wind flows toward the wind farm in the morning on a winter day, which may be associated with the steep mesoscale slope of the terrain. Wan et al. (2010) conclude that the

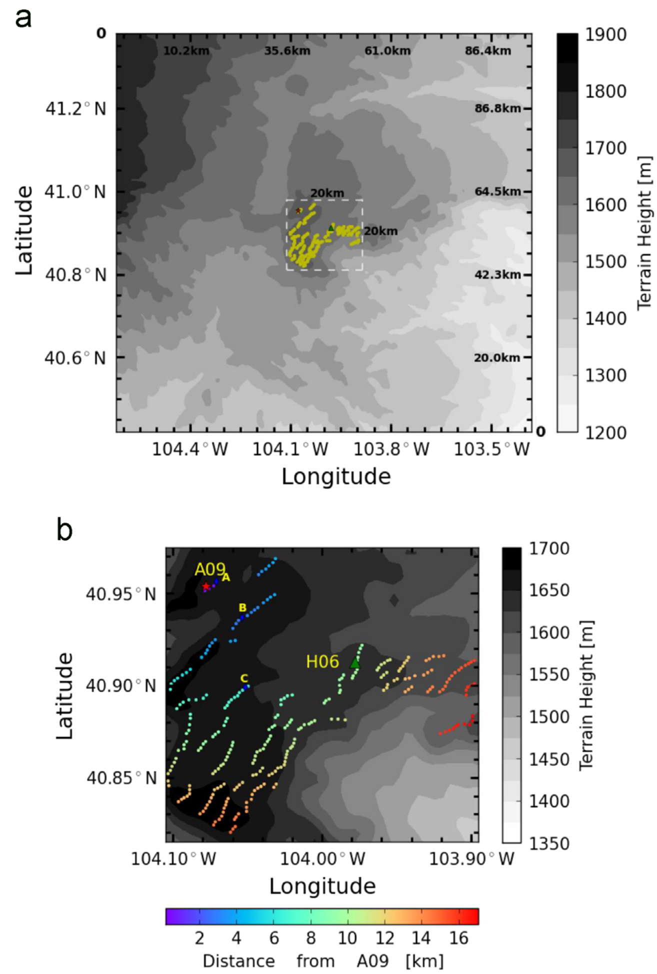


**Fig. 1.** Locations of 274 wind turbines, two meteorological towers, A09 and H06 in the study wind farm. The color-filled contours are the terrain heights (a) in and (b) around the wind farm. The distance of each wind turbine from A09 is marked with the color of each dot at the turbine location. Also indicated are the reference wind turbines (A–C) used for the correlation coefficients presented in Figs. 6–8. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**
The percentage of missing data points and the median value of the longest periods of consecutive missing data points of the nacelle anemometer time series at all the 274 wind turbines for each month.

| Month | Missing points/ total points (%) | Median of the longest periods of consecutive missing data points (h) |
|---|---|---|
| January | 2 | 0.75 |
| February | 10 | 2.75 |
| March | 22 | 10 |
| April | 32 | 43.25 |
| May | 7 | 4.25 |
| June | 15 | 1.25 |
| July | 11 | 4.75 |
| August | 7 | 2.25 |
| September | 16 | 6.25 |
| October | 10 | 5.5 |
| November | 20 | 13 |
| Total 11 months | 14 | 3.75 |