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Terrain effects on characteristics of surface wind and wind turbine wakes

Wei Tian[a,b], Ahmet Ozbay[b], Hui Hu[b,]*

[a]*School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai 200240, China*
[b]*Department. of Aerospace Engineering, Iowa State University, Ames Iowa 50010, US*

Abstract

An experimental study was conducted to investigate the interferences of wind turbines sited over hilly terrains in order to elucidate the underlying physics to explore/optimize design of wind turbines sitting over complex terrains for higher power yield and better durability. The experiments were conducted in an atmospheric boundary layer wind tunnel with wind turbines sited over two-dimensional hill models with different slope. Detailed flow field measurements were made to quantify the flow characteristics of the surface wind and wake interference among multiple wind turbines over hilly terrain.

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Keywords: wind turbine; complex terrain; wake interference; atmospheric boundary layer (ABL) wind

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1. Introduction

With the rapid development of wind energy, exploitation of more areas with high wind potential to build large wind farms has been one of the most important challenges for the wind energy community. The complex terrain are the areas with high mean wind velocities and therefore have great potential for energy production [1]. The considerable heights of most rolling hills tend to increase the mean wind velocities because of the speed-up effects on the oncoming wind field. However, the complex terrain also induce negative effects because of high wind shear, flow separation and increased levels of turbulence. Therefore, in order to utilize the high mean wind velocities and therefore increase the possible power output, and meanwhile avoid the negative effects, the understanding of detailed

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* Corresponding author. Tel.: +1-515-294-0094; fax: +1-515-294-3262.
E-mail address: huhui@iastate.edu

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surface wind characteristics over complex terrain as well as the optimum micro siting design of wind farms sited in complex terrain are greatly desired [2].

In a wind farm, the interaction of the flow with wind turbines results in the lower power output and higher fatigue loads on the downstream turbines compared with the upstream turbines experiencing free-stream conditions. Depending on the distance between the turbines and the arrangement in a wind farm, the power generation could lose up to 40% when the wind turbine operates within an array other than with free-stream flow [3-4]. The increase of fatigue loads on the downstream turbines due to the wake interference can be up to 80%, which will dramatically shorten the lifetime of the rotor blades [5]. One focus area on wind farm design is to develop the wake models in atmospheric boundary layer with various atmospheric conditions. However, most of these studies are related to the simplified flat terrain. More recently, Barthelmie et al. [6] attempt to evaluate the performance of CFD models and to examine the development of wakes in complex terrain. They proposed that there is still substantial space for using present developed wake models to predict the wake interference in wind farms sited over complex terrains. The challenges associated in the development of wake models for wind farms sited over complex terrains are the fewer quantitative measurement data of atmospheric boundary layer (ABL) wind profile and turbulence characteristics. With the large-scale wind farms tend to be installed in terrains of increasingly complexity. It clearly calls for a comprehensive study on the wake interference of wind turbines over complex terrains.

In the present study, flow characteristics of surface wind over two-dimension hill were measured to assess the effects of the hilly terrain on the characteristics of surface wind energy resource. In addition, the wake interference of wind turbines sited over hilly terrain are also assessed in order to elucidate the underlying physics of the wake interference of multiple wind turbines over the complex terrain. The quantitative measurement results of the present study cannot only be used as the database for wake model and CFD numerical simulation validation and verifications, but also used for the optimal design of turbine sitting over complex terrain for higher total power output and better durability.

2. Experimental setup

The present experiments were conducted in a large-scale Aerodynamic/Atmospheric Boundary Layer (AABL) Wind Tunnel located at the Aerospace Engineering Department of Iowa State University. The AABL wind tunnel is a closed-circuit wind tunnel with a test section of 20m long, 2.4m wide and 2.3m high. The triangular spires at the beginning of the test section and the wooden blocks covered on the wind tunnel floor were used to simulate the flow conditions similar to atmospheric boundary layer (ABL) wind under thermally neutral conditions.

Figure 1(a) shows the simulated mean velocity profile of oncoming flow at the centerline of the wind tunnel. It is known that the mean velocity profile of an ABL wind over an open terrain can usually be fitted well by using a power function or a logarithmic function. It can be seen clearly in Fig. 1(a) that the present measurement data can fit well with either the power law or the logarithmic law. The power law exponent of the curve fitting to the present measurement data is 0.16. In addition, the turbulence intensity shown in Fig. 1(b) at hub height is about 16%.

(a) (b)

Fig. 1. Atmospheric boundary layer profiles (a) mean stream-wise velocity; (b) turbulence intensity.

The wind turbine model used for the present study represents the most widely used three-blade horizontal axial wind turbines (HAWT). The rotor radius of the wind turbine model is 127 mm and the height of the turbine nacelle is 225mm above the wind tunnel floor. With the scale ratio of 1:350, the test model would represent a wind turbine in a wind farm with the rotor diameter about 90m and tower height about 80m.

The two-dimensional hill model was made by using a wooden frame with Gaussian curve covered with a piece of thin film. The geometry of the two-dimensional hill is defined by the following Gaussian curve:

$$z = h * \exp\left[-0.5\left(\frac{x}{\sigma}\right)^2\right], \sigma = L/1.1774 \tag{1}$$

where h=285mm is the height on the top of hill, L is the length measured in x direction between hill height form $h/2$ to h. The hill slope is defined as the average slope for the top half of the hill, i.e., $s=(h/2)/L$. Two hill models with slope of s=0.25 (low slope) and s=0.5 (high slope) were tested in current study. According to the study of Mason and King [3], the critical slope for flow separation occurrence over hilly terrain is around 0.3. The hill models used in current study represents two typical hilly terrains with and without flow separation on the leeward side of hill. In addition, as shown in Figure 2, five wind turbines were placed at five different positions over the hill. The detailed flow fields were measured to study the wake interference of wind turbines over hilly terrain.

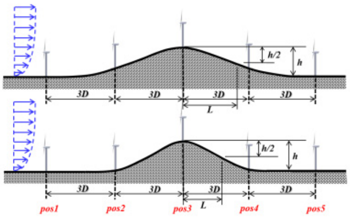


Fig. 2. Schematic of tested terrain model.

3. Results and discussions

3.1. Flow characteristics over hilly terrains

In order to examine the surface flow over hilly terrain, velocity profiles were measured at five selected positions, as shown in Fig. 2. The profiles of mean stream-wise velocity over hilly terrain with different slope are plotted in Figure 3. The velocity profile of inflow on flat terrain is also plotted for comparison. All the velocities shown in Fig. 3 are normalized with U_H, which is the hub height velocity of inflow on flat terrain.

Position 1 is located in front of the hill. It can be seen from Fig. 3(a) that below the hill height (z/H<1.27), the velocity over hilly terrain is smaller if compared with the inflow on flat terrain. The maximum difference between hilly terrain and flat terrain is near the ground. With increase of the height, this difference decrease continuously and finally disappear near the hill height. The difference of velocity mentioned above indicates that the blockage effect on the flow located in front of hill cannot be neglected. Obviously, this blockage effect caused by downstream hill will reduce the kinetic energy that the wind turbine can extract from the flow at the position in front of hill. In addition, as shown in Fig. 3(a), if the position is located far in front of hill, such as position 1, the influence of hill slope on wind velocity at that position can be ignored.

With the wind moving closer to the hill, the blockage effects become more and more apparent. For high slope hill, position 2 is located at the foot of hill, where corresponds to the maximum blockage effect. It can be seen from Fig. 3(b) that the blockage effect induce a great decrease of mean velocity for high slope hill. At hub height this decrease of wind velocity can reach to 12%.

For low slope hill, the decrease of wind velocity caused by blockage effect at position 2 is much smaller when compared with high slope hill, which means even in front of hill, the low slope hill can provide more kinetic energy which can be extracted by wind turbines. Comparison of velocity profiles at position 1 and position 2 shows that the increase of blockage effect is mainly occur in the region near the ground (z/H<0.5). In the region of rotation disk of the turbine blades, the difference between wind velocities at position 1 and position 2 is very small. Thus, for low slope hill, the kinetic energy can be extracted by wind turbines located in front of hill change slightly with the flow moving close to the hill.

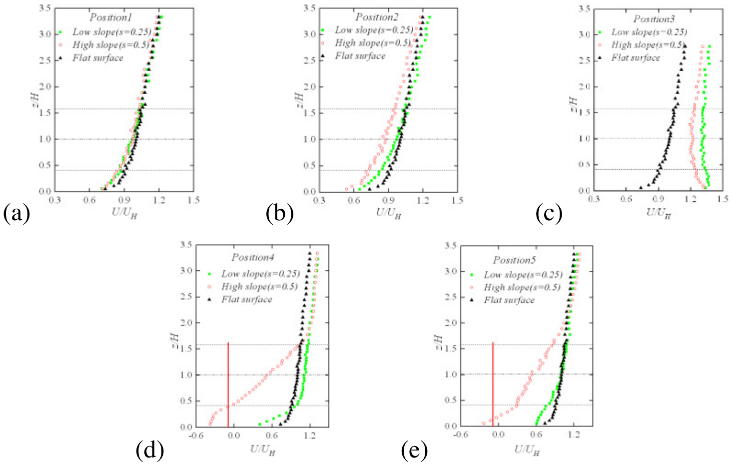


Fig. 3. Comparison of mean stream-wise velocity profile at hilly terrain and flat terrain (Horizontal dotted lines represent the top and bottom rotor tip height. The dash-dotted line represents the hub height) (a) pos1; (b) pos2; (c) pos3; (d) pos4; (e) pos5.

In addition, it should be noticed that in Fig. 3, z=0 is always located at the bottom of wind turbine model. At different position over the hilly terrain, z=0 is fixed on the surface of the hill, which is also the height of wind turbine bottom. Thus, the change of velocity on the hill shown in Fig. 3 is contributed by two parts. One is due to the change of the height at different position over hill. Another one is the influence of topography on the flow characteristics of wind over hilly terrain, such as the speed-up effect. Because position 2 is located very close to the foot of hill, there is no enough space for the wind speed to accelerate. Thus, the speed-up effect can be neglected at this position. The increase of velocity above z/H=2.0 shown in Fig. 3(b) is mainly caused by the change of height (the hill height at position 2 is 0.29h for low slope hill).

With the flow moving to the top of hill, the blockage effect will decrease gradually and finally disappear when the flow move on the top of hill. At the same time, the speed-up effect will increase continuously and reach to maximum. Figure 3(c) shows the velocity profiles on the top of hill. A distinguished increase of velocity can be seen in Fig. 3(c) when compared with the velocity profile on flat terrain. As mentioned above, this increase of velocity is caused by two parts. Here the velocity at hub height will be used to analysis the contribution of this two parts. The distance between hub height on top of hill and the ground of flat terrain is h+H=510mm. At this height the normalized velocity on flat terrain is 1.08. The normalized velocities at hub height are 1.32 for low slope hill and 1.22 for high slope hill. The increase of wind velocity at hub height due to speed-up effect is about 22% for low slope hill and 13% for high slope hill. For low slope hill, the wind speed has longer distance to accelerate when compared with high slope hill. Thus, the speed-up effect is more evident on low slope hill, as shown in Fig. 3(c). In addition, the velocity profiles on top of hill are quite different from atmospheric boundary layer flow, which is similar to the uniform flow. This change of mean velocity profile will decrease the fluctuation of wind loads acting on the wind turbine.

It is known that there is strong adverse pressure gradient over downhill and behind the hill. As shown in Fig. 3(d), a great decrease of wind velocity caused by adverse pressure gradient can be observed on the high slope hill at position 4. The velocities near the ground are in the opposite direction, which indicates that the flow would not overcome the high adverse pressure gradient in the back of hill. Thus, the wind turbine sited in position 4 is operating in the region of separation flow. The kinetic energy can be extracted by wind turbine in this region will decrease dramatically. For the low sloped hill, as shown in Fig. 3(d), the adverse pressure gradients is much smaller when compared with high slope hill, and there is no flow separation after the hill. In the region of rotation disk of the turbine blades, the increase of velocity is obvious when compared with inflow on flat terrain. After top of hill, the wind speed will decrease with flow moving downstream. This decrease of velocity is highly dependent on the slope of hill. If the slope is low enough, the velocity behind the hill can even be higher than that on flat terrain.

With flow moving far away from the hill, the influence of hilly terrain on the surface flow will decrease gradually. However, as show in Fig. 3(e), the change of wind speed after hill is highly dependent on the slope of hill. For low slope hill, the mean velocity continue to decrease from position 4 to position 5. At position 5, expect the region near the ground, the flow almost return to the atmospheric boundary layer inflow on flat terrain. Thus, it can be seen that the influence of hill with low slope on the surface flow can decrease in a short distance when flow moving away from the hill. For high slope hill, as shown in Fig. 3(e), a great decrease of velocity still exist at position 5 when compared with inflow on flat terrain. It can be seen that the separation flow over high slope hill needs a much longer distance to recover.

As mentioned by Sanderse [5], turbulence intensity is the primary cause of fatigue failure and is used as an estimation of the fatigue loads acting on wind turbines. It is known that onshore wind farm sited in complex terrain is usually accompanied with high turbulence intensity. Hence, the fatigue failure of wind turbine is one of the most important aspects in onshore wind farm. The influence of hilly terrain on stream-wise turbulence intensity is shown in Figure 4. The turbulence intensity of inflow on flat terrain is also plotted for comparison.

As shown in Fig. 4(a), the enhancement of turbulence intensity can be clearly seen below the hill height. Thus, the blockage effects of downstream hill mention above not only decrease the flow velocity, but also enhance the turbulence intensity. At hub height, the turbulence intensity is about 17% over flat terrain and 18% over hilly terrain. This enhanced turbulence intensity will increase the fluctuation of wind loads acting on wind turbine.

For high slope hill, as mentioned above, position 2 is located at the foot of hill, where corresponds to the maximum blockage effect. The enhancement of turbulence intensity at position also reach to maximum. The increase of turbulence intensity not only occur in the region below hill height, but also can expend to the height of z/H=2.0. For low slope hill, the blockage effect on turbulence intensity is much smaller. The turbulence intensity is almost identical with the inflow on flat terrain. It should be notice that above z/H=2.0, the decrease of turbulence intensity on low slope hill is mainly caused by the change of hill height at position 2, which is about 0.29h higher than the ground of flat terrain.

With the flow moving to the top of hill, the turbulence intensity will decrease gradually at reach to the minimum. As shown in Fig. 4(c), the turbulence on top of hill is much lower than that on flat terrain. Also, this decrease of turbulence intensity is contributed by two parts. For example, the turbulence intensity on the hub height is about 13% for low slope hill. At the same height of flat terrain (h+H=510mm), the turbulence intensity is about 15.5%. Thus, the decrease of turbulence intensity caused by the influence of hilly terrain can reach to 19%. In addition, it can be seen from Fig. 4(c) that the decrease of turbulence intensity is more evident on low slope hill.

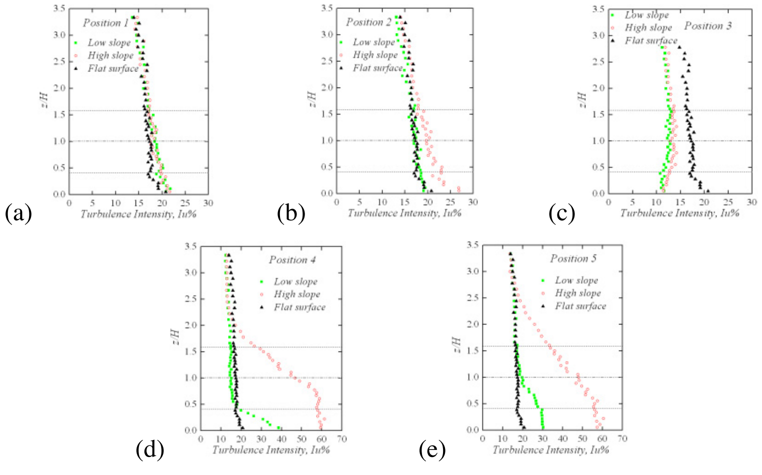


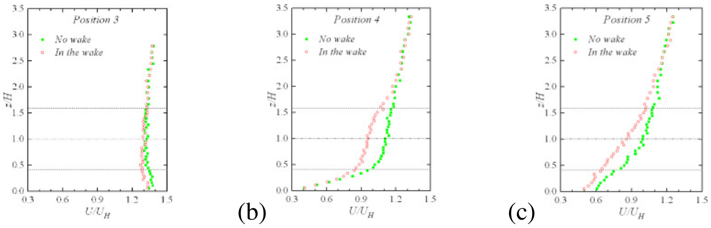
Fig. 4. Comparison of stream-wise turbulence intensity profile at hilly terrain and flat terrain (a) pos1; (b) pos2; (c) pos3; (d) pos4; (e) pos5.

As shown in Fig. 4(d) and 4(e), the behavior of turbulence intensity shows great different between high and low slope hill. For high slope hill, the flow separation make the turbulence intensity increase dramatically. In addition, with the expansion of flow after top of hill, the region with high turbulence intensity become larger and larger. At position 5 this region can even reach to the height of z/H=2.7, where is much higher than the height of hill. For low slope hill, the increase of turbulence intensity after top of hill shown in Fig. 4(d) is much slower. At position 4, where is located at the downhill, the turbulence intensity is even lower than that on flat terrain except the region very close to the ground. With flow move away from hill, the expansion of flow with high turbulence intensity can also be observed. However, as shown in Fig. 4(e), the expansion region is just limited below the height of hill. From above analysis, we can see that the effect of enhanced flow turbulence on wind turbine sited after top of low slope hill is slight when compared with high slope hill.

3.2. Wake interference of wind turbines over hilly terrains

A modern wind farm usually consists of multiple wind turbines arranged in an organized pattern or arrays. The effect of interaction between wind turbines may have serve implications on the downstream turbines which are located in the wake of upstream ones. The wake interference effects will highly decrease the power output and increase the fatigue loads of wind turbine sited in the wake. If the wind farm is located over complex terrain, the performances of wind turbines sited in the wind farm are not only influenced by topography, but also affected by the interaction of the flow with wind turbines.

In Figure 5, the velocity profile in the wake is compared with no wake at selected positions for low slope hill. All the velocity are normalized with the hub height velocity of inflow on flat terrain (U_H). The velocity deficit shown in Fig. 5(a) indicates that the wake effect is insignificant on top of the hill. The maximal velocity deficit occur below z/H=0.5. It should be noticed that the region below z/H=0.5 on top of hill is in the wake of upstream turbine. Above the height of z/H=0.5, only slight velocity deficit can be observed.



(a) (b) (c)

Fig. 5. Comparison of velocity profiles with and without wake for low slope hill (a) pos3; (b) pos4; (c) pos5.

After the top of hill, the flow will expend with the decrease of the hill height. Therefore, the wake will also spread to larger region in vertical direction. This change of flow after top of hill will enhance the wake effect. As shown in Fig. 5(b) and 5(c), the wake effect is significant at the positions at downhill (position 4) and behind the hill (position 5). The trend that the wake spread in vertical direction can be easily seen in Fig. 5(b) and 5(c).

(a) (b)

Fig. 6. Comparison of velocity profiles with and without wake for high slope hill (a) pos3; (b) pos5.

Figure 6 shows the comparison of mean velocity profiles with and without wake at selected position over high slope hill. It can be seen that the velocity deficit caused by turbine wake is not obvious at the positions on top of hill, which is the same as low slope hill. Behind high slope hill, the separation flow caused by the strong adverse pressure gradient play the dominate role in the surface flow characteristics. Compared with the great velocity deficit caused by separation flow, the influence of upstream turbine wake is quite small and can be ignored. As shown in Fig. 6(b), the two velocity profiles are nearly identical.

4. Conclusion

The surface flow characteristics are highly dependent on the slope of the hill. The greatest difference appears in the region behind top of hill. For low slope hill with no flow separation behind top of hill, the mean velocities in this region change at a low rate. For high slope hill, the flow separation caused by strong adverse pressure gradient will dramatically decrease the mean velocity. If the wind farm is located over hill terrain, the wake effects will also be highly influenced by the slope of hill. For low slope hill, the wake effect will be enhanced by the flow expansion with decrease of hill height after the top of hill. However, for high slope hill, the wake effect is not obvious. The flow characteristics are mainly determined by the change of topography.

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