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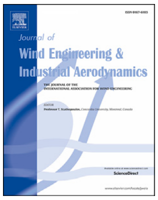

An experimental investigation on the aeromechanics and wake interferences of wind turbines sited over complex terrain

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ABSTRACT

An experimental study was conducted to investigate the aeromechanics and wake interferences of wind turbines sited on two-dimensional hills with different slopes. First, detailed flow field measurements were correlated with dynamic wind load measurements to reveal the effect of topography on the performance of an individual wind turbine sited at different locations on hilly terrains. Compared to a flat surface, wind turbines sited on a hilltop not only generate more power due to the speed-up effect but also experience reduced fatigue loads due to the decreased level of the turbulence on a hilltop. It was also found that a wind turbine located downstream of a steep hill has a greater likelihood of experiencing extreme wind loads compared to one on a gentle hill. Second, wind turbine wake characteristics and their effects on the dynamic wind loads of downstream wind turbines were also assessed. The effect of an upstream turbine wake on the wind turbine sited on a hilltop was found to be much less significant compared to a wind turbine on a flat surface. In addition, while the wake of an upstream turbine sited on hilltop has a significant influence on the dynamic wind loads of a downstream turbine sited behind a gentle hill, the effect of an upstream turbine wake on a downstream turbine placed behind a steep hill was found to be almost negligible. The quantitative measurement results of the present study not only provide a database for the validation of wake models and numerical simulations but can also be used to optimize the layout of wind turbines sited on complex terrain for higher power yield and better durability.

1. Introduction

Wind energy, as a renewable and clean energy source, has received increased attention in recent years due to its vast potential and availability. With the rapid increase of installed wind energy capacity, the exploitation of additional areas with high wind potential is one of the most important challenges faced by the entire wind energy community. The considerable heights of most rolling hills in complex terrains tend to increase the mean wind velocities due to the speed-up effects. Numerous wind farms in the planning stages are to be located in complex terrains. However, complex terrains also induce negative influences due to the increased turbulence level, high wind shear and flow separation. Therefore, in order to utilize the high mean wind speeds to increase the power production while avoiding the negative influences, the understanding of detailed surface wind characteristics over complex terrains and the optimum micro-siting design of wind farms sited in complex terrains are greatly desired.

It is known that complex terrains have a significant influence on the local wind environment, including wind speed, wind direction, and wind turbulence. These parameters are all highly affected by the local topography, and they usually change significantly over a short distance. Many studies related to the turbulent flow over complex terrains have been performed since the 1970s. Taylor and Gent (1974) and Jackson and Hunt (1975) presented analytical solutions to model the turbulent flow over two-dimensional, smooth hills. Their theories were then extended by many other researchers, including Mason and Sykes (1979), Bradley (1980) and Hunt et al. (1988a, 1988b). Mason and Sykes (1979) developed an analytical solution for three-dimensional topography that become the basis for the models developed by Walmsley et al. (1982) and Taylor et al. (1983). The rapid distortion theory was introduced by Britter et al. (1981) to estimate the change in turbulent properties of the flow over hills. An important feature of flow over hills is the speed-up effect. The speed-up effect along the upstream slope of the hill is mainly dominated by the pressure gradient along the streamline. This pressure gradient was found to be highly related to the hill slope, which has been demonstrated by several theories (Jackson and Hunt, 1975;

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Hunt et al., 1988a). By applying linear theory to a gentle hill, Jackson and Hunt (1975) predicted that the speed-up at the hilltop is approximately proportional to the hill slope. Later, Lemelin et al. (1988) proposed a simple empirical model to estimate the wind speed-up based on computational and wind tunnel data obtained for various shapes of hills. By utilizing computational fluid dynamic (CFD) with the $k-\varepsilon$ turbulence model, Paterson and Holmes (1993) established the values of topographic multipliers to estimate the wind speed-up over hills. Miller and Davenport (1998) quantified the effect of topography and compared the observed speed-ups with those predicted by the Canadian and UK wind loading codes. Weng et al. (2000) incorporated the effects of surface roughness and non-linearity on the fractional speed-up over hilly terrains. Pellegrini and Bodstein (2004) proposed a new analytically-derived expression to predict the height of the maximum speed-up for atmospheric boundary layer (ABL) flows over low hills. A CFD trained neural network for computing the speed-up ratio for flow over hills was introduced in the studies of Bitsuamlak et al. (2006, 2007). Finnigan and Belcher (2004) and Harman and Finnigan (2010) develop an analytical model for ABL flow over a hill that is covered with a vegetation canopy. They indicated that the perturbations to the flow within the canopy are driven by the pressure gradient associated with the flow over the hill. In addition, a majority of the CFD studies were performed by means of the Reynolds-Averaged Navier-Stokes equations (RANS) and Large Eddy Simulation (LES) (Bowen, 2003; Uchida and Ohya, 2003; Bechmann and Sørensen, 2011; Balogh et al., 2012). In addition to these theoretical and CFD studies, numerous wind tunnel experiments and field measurements have been also performed. Britter et al. (1981) measured the stream-wise velocity over a bell-shaped, two-dimensional hill placed in a neutrally stratified boundary layer. The results agree well with the model proposed by Jackson and Hunt (1975). Furthermore, Coppin et al. (1994) investigated the flow field over Cooper's Ridge for various atmospheric stability conditions, and found that the speed-ups over the ridge show significant differences between neutral and non-neutral conditions. Lubitz and White (2007) found that wind speed-up could vary significantly depending on the approaching wind direction.

In comparison to the flow characteristics on a gentle hill, the behavior of the mean and turbulent characteristics of the flow on the lee side of a steep hill fundamentally differ due to the flow separation. A number of experimental and numerical studies were conducted to better understand the flow characteristics over steep hills. Ferreira et al. (1991, 1995) studied the turbulent isothermal flow around two-dimensional sinusoidal hills and indicated that the extension of the recirculating region was strongly dependent on the hill shapes. Kim et al. (1997) compared the low Reynolds number model with the $k-\varepsilon$ model and found that the former predicted the flow separation on the lee side of a steep hill much better. Ying and Canuto (1997) numerically studied turbulent flow over two-dimensional hills and proposed a second-order closure model which accounts for advection, diffusion, production and dissipation processes to represent the Reynolds stresses distribution over hills. Carpenter and Locke (1999) performed a wind tunnel study of the flow over a variety of hill geometries and compared mean speeds with the results calculated using CFD. Athanassiadou and Castro (2001) investigated neutral flow over a series of sinusoidal hills and compared the results with linear theory predictions for the flow in the inner region and aloft. Cao and Tamura (2006) indicated that the surface roughness increases the speed-up ratio above the crest. Later, Cao and Tamura (2007) studied the effects of sudden changes in roughness on the turbulent flow over a steep hill, and found that the speed-up ratio depends strongly on the surface conditions in the middle layer, with the inviscid but rotational part of the outer layer defined by Hunt et al. (1988a). Røkenes and Krogstad (2009) experimentally demonstrated that even for the hill models with steep slope, the speed-up of the flow on the hilltops still approximately has a proportional relationship with average slope of the hill. These studies have given insight into the turbulent flow over hills, and the related data have been embodied in numerous wind loading codes (AIJ, 1996; ASCE, 2002, 2005, 2010; AS/NZ1170.2, 2002; CEN, 2004). This foundation enables us to further explore the effects of mean and turbulent flow characteristics on the performances of wind turbines placed at different locations over a hill.

In addition, the interaction among turbine arrays in a large wind farm is an important aspect that needs to be considered because it reduces power generation and creates higher fatigue loads for the wind turbines experiencing wake flow compared to the upstream turbines under free-stream conditions. The turbine wake is characterized by a substantial stream-wise velocity deficit, which leads to less available wind energy for the downstream turbines to harvest. It also causes enhanced turbulence intensity, which increases the fatigue loads acting on the downstream turbines. It has been found that the power generation of a wind turbine could be reduced by up to 40% when the wind turbine operates within the wake of an array rather than within free-stream flow (Corten et al., 2004). The enhanced turbulence intensity can dramatically shorten the lifetime of the wind turbine (Van Binh et al., 2008; Sanderse, 2009). One area of focus in wind farm design is to develop robust wake models with various atmosphere conditions. However, most of these studies are related to flat surfaces. Barthelmie et al. (2007) and Politis et al. (2012) attempted to evaluate the performance of those models and to examine the evolution of turbine wakes over complex terrains. They found that those wake models could not be used to accurately predict the wake interference in wind farms on complex terrains. The challenges associated with the development of wake models for wind farms sited on complex terrains are that there have been few quantitative measurements on the wake interferences of the wind turbines sited over complex terrains.

In the present study, the flow characteristics of the surface wind over two-dimensional hills with different slopes were studied to assess the characteristics of surface wind energy resources over hilly terrains. The dynamic forces acting on the model wind turbines mounted at different positions on hilly terrains were also measured. The quantitative flow field measurements were correlated with the wind load measurements to investigate the effects of topography on the performance of the wind turbines sited on hilly terrains. In addition, the wake interferences of wind turbines sited on hilly terrains were assessed. The quantitative measurement results of the present study can not only be used as a database for the development of wake models and numerical simulations, but can also be used in designing the optimal layout of wind farms located in complex terrains.

2. Experimental setup

2.1. Atmospheric boundary layer wind tunnel

Experimental studies were performed in a large-scale ABL wind tunnel located at the Aerospace Engineering Department of Iowa State University. Fig. 1(a) shows a sketch of the ABL wind tunnel. The wind tunnel has a contraction section with a 4.8:1 area ratio upstream of the test section along with a set of honeycombs, wire meshes, and a cooling system to provide uniform airflow into the test section. The wind tunnel is operated as a closed return loop. The test section is 20 m long, 2.4 m wide and 2.3 m high. The maximum wind speed is 45 m/s in the test section. During the experiments, the triangular spires at the beginning of the test section and wooden blocks spaced on the wind tunnel floor were used to simulate the flow conditions similar to ABL wind under thermally neutral conditions. As shown in Fig. 1(b), five spires with aspect ratio of 0.16 are equally distributed at the beginning of the test section, on a plane normal to the flow direction. A thin plate with the height of 200 mm are mounted on the wind tunnel floor and connected with the five spires. In addition, surface roughness elements with different size and spacing are covered on the wind tunnel floor. The parameters of the surface roughness elements are listed in Table 1.

In the present study, Cobra Probe anemometry was used to characterize the ABL inflow condition. Mean velocities and turbulent