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Wind-tunnel and field investigation of the effect of local wind direction on speed-up over hills

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Abstract

Measurements of flow past simulated sinusoidal hills were taken in an atmospheric boundary layer wind tunnel (ABLWT) that modeled typical full-scale complex terrain for many wind turbine locations in the Altamont Pass, California, USA. Velocity profiles and speed-up factors for several model hills were determined. All hills modeled had the same height and sinusoidal cross-section, and length-to-width aspect ratios of infinity, four and one. Each of the three models was tested with approach wind directions from 0° to 90°, in 15° increments. It was observed that speed-up can vary significantly depending on the approaching wind direction. The effect of wind direction on speed-up was also investigated using field data from a site in the Altamont Pass. Average speed-up factor was found to vary significantly at the site in time, and as a function of atmospheric stability.

Keywords: Wind tunnel; Complex terrain; Speed-up; Wind direction; Hill; Altamont Pass

1. Background

Much work has been done developing simplified models for predicting wind "speed-up" in complex terrain. Speed-up is the increase of near-surface wind speed above a hill as compared to the wind over a flat surface at the same height above the surface.

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Non-dimensionally it is expressed as the fractional speed-up ratio:

$$\Delta S = \frac{U(z) - U_0(z)}{U_0(z)}, \tag{1}$$

where U is the wind speed at a height z above the hill, and U_0 is the upstream speed of the hill at the same height. It is assumed that the approach to the hill is a flat surface with the same surface roughness as the hill.

Jackson and Hunt (1975) developed an analytical method to predict speed-up over a two-dimensional, smooth hill without flow separation, which was subsequently improved (Hunt et al., 1988). Jackson also examined the implications of this approach, as well as wind-tunnel and numerical methods, for evaluating potential wind turbine sites (Jackson, 1979). Other researchers have made extensions to the Jackson and Hunt methods. For example, Mason and Sykes (1979) extended the method of Jackson and Hunt to a single three-dimensional axisymmetric hill. The body of work based on Jackson and Hunt remains essentially the only satisfactory analytical method of estimating speed-up over hills.

Kaimal and Finnigan (1994) report that the results of Jackson and Hunt were used to formulate a set of widely used simple guidelines to estimate the maximum speed-up ΔS_{max} expected to be observed over simple topographic features with slopes low enough to not experience flow separation (i.e., geometric divergence angles of less than 15–18° from the mean flow direction)

$$\Delta S_{max} \approx 1.6h/L_1 \quad \text{for axisymmetric hills,} \tag{2a}$$

$$\Delta S_{max} \approx 2.0h/L_1 \quad \text{for 2D ridges.} \tag{2b}$$

Here L_1 is the horizontal distance from the hill peak of height h to the point on the slope at height $h/2$ (the "half-height" of the hill). This set of equations is generally considered to be accurate to $\pm 15\%$.

There have been numerous experimental studies that investigated speed-up over two-dimensional hills. Gong and Ibbetson (1989) performed wind-tunnel tests on a two-dimensional ridge and a circular hill, both with cosine squared cross-sections. Miller and Davenport (1998) conducted wind-tunnel tests of two-dimensional model hills, and presented tables of speed-up values for different approach slopes and upwind conditions. Weng et al. (2000) also present guidelines for two-dimensional hills, based on hill geometry and surface roughness; additionally, they report the results of several wind-tunnel tests. Taylor (1998) conducted numerical simulations of flow over low and moderate slope hills, and presented an equation to predict speed-up based on hill parameters. Kim et al. (1997) experimentally and numerically investigated the effects of hill slope on speed-up over two-dimensional hills of sinusoidal cross-section. In numerical simulations and field studies of actual hills, Kim et al. (2000) observed that the flow field over a hill was affected by the presence of other hills nearby, and that these hills must be included for accurate results.

Further complicating matters, flow separation occurs in the lee of steep hills (Jackson, 1979). Finnigan (1988) compiled separation data from multiple field and wind tunnel studies. Separation did not occur when maximum slopes were less than 0.27 (15°), always occurred when maximum slope was at least 0.32 (18°), and was intermittent when slopes were between these values. For two-dimensional, sinusoidal hills, Kim et al. (1997) and Miller and Davenport (1998) both used the criterion that separation occurred for hills with