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Experimental and theoretical investigation of tower shadow impacts on anemometer measurements

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A B S T R A C T

The tower supporting an anemometer modifies the local wind field and anemometer measurements. In wind energy resource assessment, tower-induced flow modification contributes a non-negligible amount of uncertainty to the wind resource assessment. The effect of wind speed averaging period on anemometer measurement errors was investigated using high resolution sonic measurements from two sonic anemometers on a tubular tower. Measurements were post-processed into equivalent datasets that differed only by averaging periods. Averaging period only impacted the measured magnitude of the wake, while little effect was seen outside the wake region for data averaging periods between 15 s and 1 h. A model is proposed to remove tower shadow effects from anemometer data using a potential flow solution in the region outside the tower wake and assuming the tower wake is Gaussian and turbulent. An untuned version of the model reproduced the main features of tower-induced flow modification including the turbulent wake, but was not accurate enough to provide a useful correction for wind resource assessment purposes. Fitting model parameters using measured data was found to be a practical way to partially correct wind data from a pair of anemometers in which one fails or becomes unreliable.

1. Introduction

Tower-mounted anemometers are the standard method of collecting wind data for wind energy resource assessments. Locating an anemometer on the top of the tower is ideal since there are no wind directions that result in the anemometer having tower structure upwind, and flow distortion is below 2% (Perrin et al., 2007). However, this configuration is often not possible. If anemometers are needed at heights other than the tower top, or more than one sensor must be placed at the tower top, an anemometer will be mounted on the end of a horizontal boom extending horizontally outwards from the tower. The anemometer must be properly positioned at the end of the boom, so that it projects upwards high enough to avoid flow distortions caused by the boom. The effect of the boom on the flow field can become significant if the anemometer is less than 15 boom diameters above the boom (Perrin et al., 2007).

The presence of the tower induces a local wind field different from the ambient flow. Field and wind tunnel measurements have confirmed the common characteristics of the flow field around a meteorological tower (Pedersen et al., 1992; Barthlott and Fielder, 2003; Bartholy and Radics, 2005; Cermak and Horn, 1968; Dabberdt, 1968; Izumi and Barad, 1970; Wucknitz, 1977). Directly upwind of the tower, wind speeds are reduced relative to ambient. Laterally local wind speeds are increased. Continuing around the tower toward the downwind side, wind speed continues to increase until the edge of the tower wake is approached. Within the region $\pm 30^{\circ}$ of the downwind direction is the tower wake region with greatly reduced wind speeds and increased turbulence.

To avoid measurement errors due to these flow distortions, the anemometer should be located as far from the tower horizontally as practical. NREL suggested minimum distances of three and six tower diameters for lattice and tubular towers respectively (Bailey and McDonald, 1977). IEC 16400-12-1 Appendix G (IEC, 2005) includes formulae to estimate the velocity deficit experienced by an anemometer as a function of distance upwind from a boom, and suggest that a distance of 5.7 times tower width will keep velocity deficit to less than 0.5% for a lattice tower of 0.5 porosity. Overall, a minimum distance of seven tower widths is considered to be conservative (Hansen and Pedersen, 1999). Note that in practice, boom length is limited by increasing boom size (which can also cause interference) and the need to rigidly support an anemometer.

In all of the above-cited publications, measurements within the tower wake region are excluded from consideration, since departures of mean velocity and turbulence from ambient within the wake are an order of

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magnitude greater than perturbations of the flow in other regions around the tower. Common practice is to not use anemometer data from wind directions that put the anemometer in the tower wake. However, cases where the wake region is unavoidable do arise. For small wind turbines, wind resource assessments and performance verifications are often constrained to a single anemometer. Placing two boom-mounted anemometers at the same level on different sides of a tower keeps at least one anemometer out of the wake region for all wind directions, however measurements from both anemometers must still be assimilated in a consistent manner. In the event of a sensor failure, there are limited options for using data from the remaining sensor to characterize wind speeds from all directions, including the wake region of the remaining anemometer.

A model that can remove the tower-induced flow distortion from anemometer measurements due to the tower would give a truer representation of the wind climate at a site. Development of a practical model to correct anemometer measurements for tower-induced flow perturbations would help address these needs, and is the purpose of this study. It is also important for models to be practically useful, and so any model should be implementable in spreadsheet or wind analysis software.

2. Flow field around a tower

Towers for meteorological or wind energy measurements are typically of two types: tubular towers, in which a single vertical circular tube is supported by one or more sets of guy wires, and lattice towers, in which three or four vertical members are connected by a network of smaller cross-members. The latter type may be guyed or freestanding. Anemometer booms have also been affixed to more massive pre-existing structures (e.g. (Bartholy and Radics, 2005)), however these installations will not be considered here.

Tubular towers consist of a single round tube supported by guy wires. Depending on the height of the tower, the tube diameter is typically in the range of 5 cm–25 cm. The wind field around the tower can be approximated as the flow around a two dimensional circular cylinder. Limiting consideration to wind speeds greater than the typical wind turbine cut-in speed of 4 m/s, the Reynolds number based on tube diameter is greater than 10,000, and while the flow around the tube will be laminar, the far wake behind the tube will be turbulent (Simiu and Scanlan, 1978). Flow around the tube begins transitioning from laminar to turbulent at a Reynolds number of approximately 3×10^5, which results in delayed separation and a narrower wake region. For a 25 cm diameter tower, this represents a wind speed of only 8 m/s, and therefore this phenomenon will be expected to have an impact for wind resource assessment purposes.

Lattice towers consist of many discrete elements each generating a discrete wake, however, outside of a near field region the flow field can be approximated as the wake of a single bluff body. Measurements at a lattice mast at the Brookhaven National Laboratory (USA) observed the velocity deficit in the tower wake had a Gaussian cross-section at anemometers spaced less than one tower width from the tower (Dabberdt, 1968). Both velocity deficit in the wake, and speed-up lateral to the tower, were independent of wind speed and slightly dependent on Richardson number. However, Fabre et al. (2014) showed a Gaussian cross section does not always occur at these distances, and non-Gaussian wake distributions could extend much further from the tower.

Flow around a two dimensional bluff body is one of the most studied problems in fluid mechanics. The width of a two-dimensional turbulent plane wake varies as the square root of distance downwind of wake origin (Schlichting and Gersten, 2000). This means that specifying a wake-impacted region as a function of wind direction angle (where width varies linearly with distance downwind) would be conservative as the distance downwind increases.

Wucknitz (1980) found a potential flow model could predict the wind speed error of a boom-mounted anemometer, but noted that Reynolds number dependency should exist even in this case. Wucknitz subsequently refined his model with an adjustment for the size of the wake, which is Reynolds number dependent (Wucknitz, 1980). A similar approach, using a laminar flow predicted wind field to correct wind speeds measured by anemometers, was employed at a large diameter tower in Hungary, although in this case multiple anemometers were available (Bartholy and Radics, 2005). Computational fluid dynamics has also been applied using an actuator disk approach (Pedersen et al., 1992; Hansen and Pedersen, 1999). The potential approach has the advantage of being easier to implement for new anemometer installations, and both methods give results for flow distortion outside the wake region that are in overall agreement with each other and measurements. While it is possible to use more complex methods such as large eddy simulation for specific situations, more intensive approaches are unlikely to result in a significantly useful improvement in accuracy, especially if the goal is to be able to apply results to different anemometer installations for which only general data would be available for model initialization and boundary conditions.

Orlando et al. (2010) investigated wind speed measurement errors introduced by tower shadowing of cup anemometers by studying the readings of anemometers in a wind tunnel at a high sampling rate. Collecting wind speeds at a rate of 128 Hz, velocity deficits caused by the wake were found to be upwards of 35%. The effect of the wake was found to be at its greatest when the anemometers were at an angle of 2°–5° from the centerline of the tower and not directly in line as was assumed. It was determined that this observation was due to the physical geometry of the rotating cup anemometers in the symmetric wake.

Omitting wind speeds less than 3 m/s can greatly reduce the amount of variation in the measured data when analyzing the deficits and speed-ups experienced by anemometers (Farrugia and Sant, 2013). Farrugia and Sant (2013) found that noticeable data distortion occurred in cases when the speed magnitude was less than approximately 3 m/s. They also determined that when measuring wind speeds using pairs of collocated anemometers, the Levenber-Marquardt algorithm could be used to generate lost or missing data in the event that one of the devices was damaged or failed. This method uses the modified algorithm to develop the absent readings based off the measurements of the remaining anemometer (Farrugia and Sant, 2013).

Continuing their work, Farrugia and Sant (2014) further studied the effects of data filtering methods in order to gain a more accurate wind speed model at intermediate heights. By removing data from the flow acceleration regions of the masts as well as from the interior of the wake region, error was minimized and more accurate models were obtained. Additionally, one method excluded the readings of the anemometers under specified wind flow directions when they were at positions to the side of the mast (Farrugia and Sant, 2014). These filtering methods greatly reduced the standard deviations of the measured values, increased accuracy, and producing lower average wind speeds by comparison. It is estimated that these methods would have similar effects on other speed-dependant wind variables, thus providing more conservative models for resource potential assessments (Farrugia and Sant, 2014).

One area that has not been investigated is the effect of averaging time on wind speeds measured in wakes. Dabberdt (1968) calculated the measured mean velocity deficit as a function of wind direction, and then applied that data as a correction factor in an attempt to remove the effect of being in the tower wake from anemometer measurements. A small improvement was noted, although large uncertainty remained. It was theorized that the use of hourly average wind speeds, with no accounting for variation in wind direction at shorter timescales, and consequently variability of the anemometer position within the wake over the averaging period, was a significant contributor to this remaining uncertainty. However, to the knowledge of the authors, the effect of averaging period on wake shadow corrections does not appear to have been reported in the literature. Since wind resource assessments are typically based on 10 min or hourly average wind speeds, this area requires investigation.