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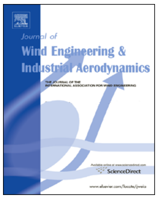

Analysis of energy dissipation and turbulence kinetic energy using high frequency data for wind energy applications

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ABSTRACT

An algorithm was developed to detect delay times in the turbulence kinetic energy (TKE) and the energy dissipation rate ε on a continuous basis (thereby identifying the highest cross-correlation coefficients between them). The Kolmogorov theory in the microscale is applied to calculate the energy dissipation rate ε through the identification of the inertial subrange. We illustrate how the variations in these two parameters happen simultaneously at all times, but indicate a time delay in those variations. The time scale in the variations of both parameters was determined and it is close to the time the air takes to circulate between the surface and the top of the atmosphere's mixed layer. High correlation coefficients are found in the three site studies from 4 am to 8 am, and from 8 pm to 12 pm. The cross-correlation function also determines delay time scales in the range of 10–20 min. The energy dissipation rate can be calculated to characterize wind variability in a particular site that might affect the performance of a wind turbine. The autocorrelation function of the TKE was also calculated to illustrate how diurnal variations can be more intense in one site than in another one. With these results, more information is generated that can be incorporated into the wind turbine's control system routines to improve its response under wind turbulence variations.

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1. Introduction

Wind data history is typically used for two main purposes: wind energy assessment and wind speed forecast. Regarding the resource assessment, the Weibull distribution is the most common tool to assess the available wind energy of a potential wind site. However, this tool is limited in that it only describes long term averages of wind speed and direction at a wind turbine location and fails to capture phenomena, such as turbulence, occurring at shorter time scales. Regarding forecasting models, several techniques of weather and wind estimation can be found in literature (Tascikaraoglu and Uzunoglu, 2014). Contemporary techniques for both assessment and prediction rely upon low frequency, periodically averaged, wind speed data.

Wind data are available in several forms, depending on the frequency of measurement and period of time averaging. Wind speed and direction are typically sampled at frequencies of 1 Hz or higher and the resulting high frequency data (HFD) are processed to calculate averages over time windows ranging from 10 min to 1 year in duration. HFD are usually discarded from the computer memory of the measurement system after these averages are calculated. In the case of wind potential assessments, wind speed averaged data are the main input to the Weibull distribution and most estimation models. In the present manuscript, HFD of three different wind sites located at confidential locations are presented. The HFD was provided by Vestas, Canadian Wind Technology Inc., an industrial partner in this research thesis. The company and the authors are convinced that valuable information is lost when HFD are discarded. In spite of this additional information contained in HFD, the authors is unaware of any current consensus or standard for HFD interpretation. Of the different avenues for HFD study, our initial approach is put on the analysis of wind variability in the frequency domain.

Wind speed estimation is typically reported in the time domain while, through spectral analysis, the characteristics of wind variability are reported in the frequency domain (Jung and Tam, 2013). The frequency domain approach for wind energy applications separates wind speed into mean and turbulent components and describes the amplitude and duration of gusts. As the temporal window of wind estimation becomes shorter (e.g. less than a minute), the estimation becomes less feasible, as the randomness

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in the wind dominates. Furthermore, predictable changes in the time domain are dominated by the synoptic and mesoscale processes in the atmospheric boundary layer, rather than the turbulent portion of the wind distribution (Stull, 1988). However, HFD can be valuable when used to describe wind variability in the frequency domain. This approach can be used to characterize wind data and even find patterns that could be used for more effective wind turbine selection and operation (Jung and Tam, 2013). According to current literature, turbulence plays a major role in the wind potential assessment in the time domain (Soler-bientz, 2011), and wind pattern characterization in the frequency domain (Rauh and Peinke, 2004; Wang et al., 2013).

Fourier analysis has been performed on wind data because it is an accessible and reliable tool to study time series in the frequency domain. It describes wind variability throughout the year and can be used to characterize patterns for a specific site study (Jung and Tam, 2013; Janajreh et al., 2013; Lee, 2014; Eggleston and Clark, 2000). Spectral analysis also relates the contribution to variance over the frequency components of a time series. As turbulence is also related to variability, it has been shown that the power spectrum analysis is highly correlated with the turbulence intensity (TI) (Stull, 1988). TI is defined as the ratio of the standard deviation over the average of the wind speed. Thus, the Fourier transform can be useful to complement wind resource potential assessment (Escalante Soberanis and Mérida, 2015). Strong TI is a problem in contemporary wind turbines, as it can lead to pitch errors and faulty behavior in the power generation (Rauh and Peinke, 2004; Janajreh et al., 2013; Burton et al., 2001; Morales et al., 2012).

There is evidence in the literature of HFD analysis to complement wind potential assessment or turbulence estimation, such as the studies carried out by Monahan, and McBean and Elliot (Monahan, 2006; Mcbean and Elliott, 1975). In the present study HFD is analyzed as a complement to current assessment tools to provide improved descriptions of the wind's turbulent component in the frequency domain. Two main concepts used in this study are the TKE and the energy dissipation rate ε. TKE is defined as the kinetic energy's component of the turbulence, while ε represent the energy loss rate in the small scale turbulence, characterized by the cascade of energy from larger length scale to small scale eddies (Stull, 1988). The degree of correlation between TKE and ε was calculated in the present study to identify the time of day when that correlation reaches a maximum. Additional examples of HFD analysis that aim to complement resource analysis can be found in studies developed at the University of Oldenburg, in Germany (Morales et al., 2012; Boettcher et al., 2003; Böttcher et al., 2007). Boettcher et al. (2003) developed a method to compare data sets from laboratory experiments and atmospheric high frequency wind data (4 Hz). They reported high intermittency of wind gust frequency occurrence which may be due to the independency of the small-scale fluctuations from the driving large-scale structures. Böttcher et al. (2007) later developed a study to characterize small and large scale variations of wind speed, particularly the increments related to gusts. For this analysis the authors used HFD measured with ultrasonic anemometers at 4 and 5 Hz. Additional data was measured through hot wire anemometer at 5000 and 100,000 Hz. Morales et al. (2012) characterized turbulent wind by means of high order statistics using HFD. Their efforts were focused on reporting probability density function of wind speed increments conditioned to certain wind speed averages, contributing to a more detailed description of turbulence variability in a probabilistic approach.

The Kolmogorov microscale is a measure that estimates the energy dissipation in the turbulence by assuming that the smallest eddies see only turbulent energy cascading down the spectrum at the rate of the dissipation. It has been widely used when the wind frequency spectrum is analyzed to identify the characteristic range of frequencies of the inertial subrange (Jung and Tam, 2013; Stull, 1988; Wang et al., 2013; Janajreh et al., 2013; Lee, 2014). It is in this region of the spectra where the energy is transferred from the larger eddies to the smaller ones via inertial processes (Stull, 1988). One way to calculate dissipation is through the energy spectrum using the Kolmogorov turbulence theory that identifies the portion of the spectrum in which the inertial subrange is observed. In the present work this theory is used to determine the dissipation rate as it varies throughout the day.

The relationship between ε and TKE has been previously studied elsewhere, highlighting the importance of the turbulence kinetic energy in describing the atmospheric boundary layer and its dynamics. Li et al. Li et al., (2014) developed a method to estimate the TI from ε and validated their model under both normal wind and typhoon conditions. Kantha and Hocking developed a method (Kantha and Hocking, 2011) to calculate the energy dissipation rate from radar measurements in the free atmosphere. Their study was focused on a better understanding of the spatio-temporal variability of turbulence. Kalapureddy et al. (2007) studied the diurnal and seasonal variations of the energy dissipation rate ε through measurements made by a lower atmospheric wind profiler. They calculated specific values of ε for a tropical region at different altitudes, focusing specifically on the convective boundary layer. It is in this region where the turbulence generates a well-mixed region, and is also where the authors observed ε had its largest values. The aforementioned methods calculate the values of dissipation from the TKE, but there is insufficient analysis of the time delay between these parameters. The existence of a time delay suggests the time in which a correlation between two parameters is still valid. This gap is addressed in the present study.

Different empirical and theoretical relations between TKE and ε for calculating their instantaneous values can be found elsewhere (Li et al., 2014; Kantha and Hocking, 2011; Kalapureddy et al., 2007). However, no information on the cross-correlation between these parameters have been reported, neither their corresponding time delay. For example, Jensen et al. (1982) have mentioned that the dissipation may occur in regions with intermittent turbulence, meaning stationary and non-stationary periods. It can be surmised that this phenomenon could involve a difference between the dissipation rate and the production of turbulent eddies:

> *"One can think of this as if the local dissipation rate runs faster than the local cascading process, such that the average supply of small enough eddies is slower than the average rate at which they are dissipated."*

Moreover, Panofsky and Dutton (1984) stated that ε can be modeled as:

$$\varepsilon = \frac{TKE}{\tau} \tag{1}$$

where τ is the time scale of those parameters. The time scale indicates when significant changes in the parameters start to occur. Both literature sources imply that there is a time scale in which the ε and the TKE experience significant changes due to diurnal and seasonal variations. It is also evident that both parameters decay together and the changes also depend on the major eddies size and wind speed average. Hereby a method is presented to evaluate the degree of correlation that leads to an estimation of turbulent wind variations. An algorithm that calculates the lagged cross-correlation coefficients between the TKE and ε was designed to estimate variations in the wind turbulence. This measure can contribute to improve the turbine's control and response to wind variability.

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