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Turbulence, a challenging problem for wind energy

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Abstract

Basic problems arising in the growing use of the wind energy are discussed. We mainly focus on problems which are related to the turbulent character of the wind. The meaning of large and meso-scale atmospheric turbulence for the energy production is discussed. We show for the wind turbulence on small scales how statistics with anomalous probabilities arise, which can be set into the context of wind gusts. Furthermore, we discuss a new method to extract a stochastic process from given data which enables a new and more profound statistical description of the complexity of turbulence and turbulent wind fields.

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Keywords: Wind energy; Turbulence; Fokker–Planck equation

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1. Introduction

The energy consumption is one of the fundamental indicators determining prosperity and poverty in our society. Nowadays $\frac{1}{5}$ of the world population consumes about $\frac{2}{3}$ of the total primary energy, which is about 400 EJ/a. About 80% of this energy is gained by the use of fossil sources. The perspective of a more balanced wealth distribution in the future requires a tremendous increase in the power demand. Limits of worldwide fossil sources are clearly seen, as well as environmental problems arising from the power consumption. Renewable energies play a central role for solving the energy

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problem in the future. Besides the hydro and solar power plants, wind energy is one of the most promising candidate. The actual cost of 1 kWh produced by wind energy is about 8 Eurocent, thus about two times the price of conventional electric energy and about $\frac{1}{5}$th of the costs for solar energy using photovoltaic. This price level as well as some political decisions have led in the last 10 years to a rapid growth of the wind energy market. At the end of 2003 the installed capacity of wind-power was over 35 GW. (Only in Germany there were 15 GW installed.) The estimated potential of wind energy, which could be used in the next decades, is about 140 EJ/a [1], if the offshore use of wind energy at reasonable locations is included. In this contribution we want to discuss some scientific challenges connected with the development of wind energy, which are based on the nature of its energy source, namely on the wind. A better understanding of the nature of the wind is the basis for a more efficient use of the wind energy.

2. Atmospheric turbulence

Wind energy is gained by wind-turbines placed in regions with strong wind, which automatically leads to situations which are dominated by strong turbulent flow situations. We will divide the problem of wind turbulence into three aspects. On long terms or on large scales, respectively, it is the turbulent weather which will determine the wind conditions and thus will determine the power production on long terms. Weather conditions are typically found on scales larger than 10 km resulting in temporal fluctuations in the range of hours and longer.

Fig. 1a shows in an exemplary way the electric power demand of a region in North Germany over one week in autumn 2002. The daily rhythm as well as the week-end (last two days) can be recognized easily. In North Germany, we have already the installation of several GW with wind turbines. Thus, a good part of the electrical power demand can be covered by wind energy. In Fig. 1b the energy demand reduced by the produced wind energy is shown. (The electricity companies are forced by law to use the produced wind energy.) On the day 20 we see that nearly 100% of the energy

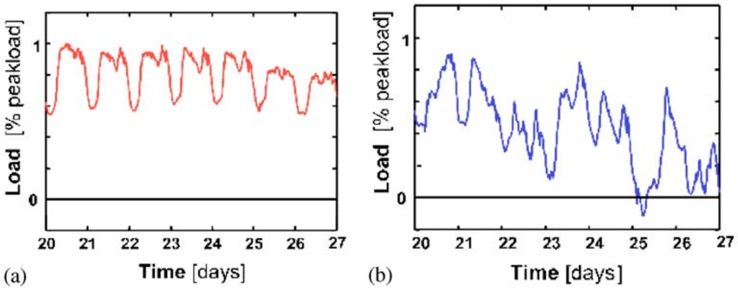

Fig. 1. Consumption of electrical power over one week in a region in North Germany (a). The data are normalized to the maximal value. In Part (b) the produced wind energy has been subtracted from the curve in part (a). Negative values indicate that more electricity is produced by the wind energy than is consumed in this region.

demand must be provided by traditional electric power plants, whereas during the day 25 there is a period, where the wind-turbines produce more electricity than demanded. Comparing these two figures it is easily seen that the control and the production of electricity by traditional power-plants becomes much more fluctuating due to the use of wind energy. The question arises how far a basic load still exists. This point becomes more complicated by the fact, that traditional big electricity power plants need several hours to change the energy production in an efficient way. Thus there is a very important need for new strategies in the electricity production. Besides a new more flexible mixture of production units, an essential aspect will be the forecast of energy production by wind (and in future by solar) energy systems. One possibility to perform such forecasts is to use the elaborated weather forecasts from the national weather services and to extract from this an energy forecast [2]. The weather forecast is usually done with a spatial resolution of some km and on a standard height of 10 m. For such a prediction of the future wind energy production, it is essential to have a good knowledge of the local wind conditions around a wind turbine or a wind farm.

The wind for a wind-turbine is influenced by the local orographic conditions, flat terrain or mountains, between woods or on the sea, just to mention some examples. Modern wind turbines nowadays have blades with more than 50 m length, thus the rotor extends up to heights of 150 m and more. This requires a profound knowledge of the wind profile up to about 200 m. These are typical meso-scale quantities of the atmospheric wind. Due to the turbulent behavior of the boundary layer it is not possible to calculate precisely the flow on these scales, which becomes even more complicated above 100 m due to the fact that at this altitude the influence of the Corriolis force comes into play additionally. Quite often the basic understanding of what is going on in such boundary layer flows is missing. As an example, we show in Fig. 2 offshore

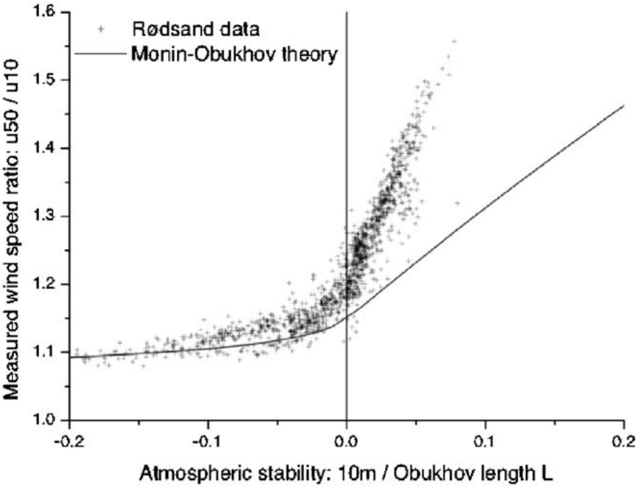

Fig. 2. Ratios of wind speed at the heights of 50 and 10 m at Rodsand in the Danish Baltic Sea versus the stability parameter 10 m/Obukhov length L; L is derived from wind and temperature measurements at the heights of 10 and 50 m; also shown is the prediction of Monin–Obukhov theory by a solid curve.

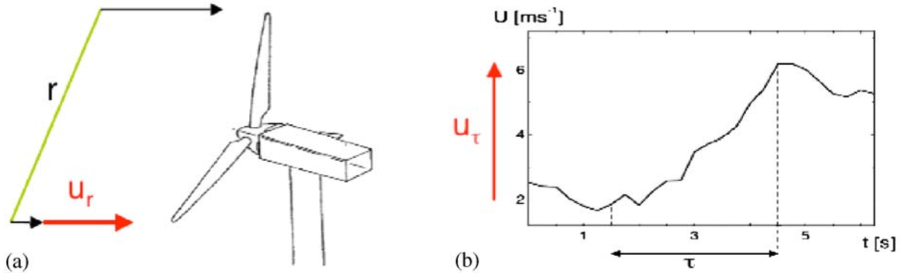

Fig. 3. In part (a) the schema of transversal wind velocity fluctuations which interacts with a wind turbine is shown. In part (b) an arbitrary excerpt of a turbulent wind speed measurement including a wind gust is shown. During 4 s the velocity increases about 4 m/s. Both figures show that velocity increments, i.e. velocity differences between two spatial points or times are meaningful sizes to characterize wind fluctuations.

measurements of the wind profile given by the ratio of the wind speeds at the heights of 10 and 50 m. In addition to the measured data, a curve is shown which represents the expected wind speed ratio from Monin–Obukhov formula, which is used with great success for onshore locations. As shown in [3] there is still not much known on the form of the mean wind profile over the sea. It is still unclear how far from the coastline the wind profile will be influenced by the effects on land. Also, the influence of waves and the thermal stratification is unclear for the case of offshore wind conditions. For onshore situations these effects of surface roughness and heat flux are well grasped by the Monin–Obukhov formula.

3. Small-scale turbulence and wind gusts

Next, we discuss small-scale aspects of the atmospheric wind turbulence. These small-scale effects cause fluctuations of the power productions which are typically in the time range below 1 h down to several seconds. The high-frequency cut-off depends on the size and the inertia of a wind-turbine. The wind fluctuations themselves may go down to a time scale well below a second. These short time or small-scale wind fluctuations cause the following different problems. The turbulent fluctuations will cause through relaxation effects other power productions than expected from the mean wind speed [4], which is usually used to estimate for example the commercial efficiency. The turbulent fluctuation will cause short-time fluctuations in the power production as well as additional mechanic loads to the machinery. Fluctuation transversal to the flow direction causes additional torques, see Fig. 3.

The problem in describing or understanding these fluctuations is based on the anomalous statistics of turbulence, also called the intermittency problem of turbulence. In Fig. 4 the probability densities of these fluctuations are shown.[1] Note that the most

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[1] This statistics was obtained from a wind measurement at the coast line of German North Sea near the town Emden. The data were measured by means of an ultrasonic anemometer at 20 m height. The sampling frequency was 4 Hz. Data were taken over 275 h in october 1997. For further details see Ref. [6].

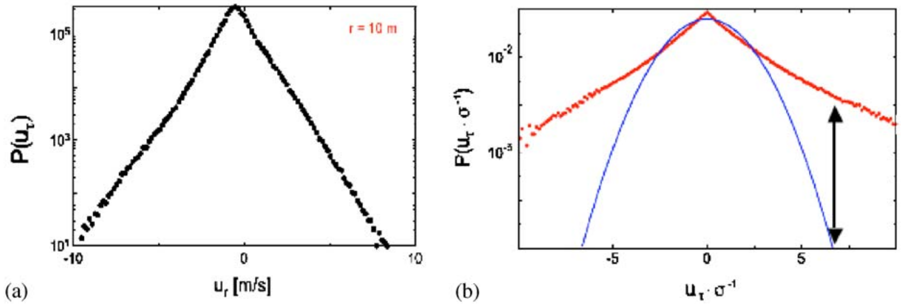

Fig. 4. (a) Probability density function (pdf) of spatial transversal velocity increments over a distance of 10 m, compare Fig. 3(a). In the right graphic (b) the pdf for $\tau = 4$ s is compared to a Gaussian distribution (solid line). Both distributions have the same standard deviation $\sigma = 0.8\,\mathrm{m/s}$ [5].

extreme events correspond to a change of the wind speed by 8 m/s during 4 s. Thus, the heavy tail of this probability corresponds to the statistics of wind gusts. Here we get the impression that wind gusts are not an independent coherent structure of the wind field, but they seem to emerge naturally in the form of heavy tailed statistics. If we compare this empirical probability distribution of the wind speed changes with a Gaussian distribution, which is uniquely given by the same mean value and the same variance, as shown by a solid curve in Fig. 4b, we see that the Gaussian distribution underestimates drastically the occurrence probability of the large events. One should note that a factor 10^6, as indicated by an arrow in Fig. 4b, corresponds to the number of hours one century consists of. Thus, the gusts we measured each hour would be expected as an event of the century for a corresponding wind field which follows Gaussian statistics. We conclude that for heavy tailed statistics the occurrence of extreme events is drastically enhanced, which is an important issue for the estimation of risks such as extreme mechanical loads for wind turbines. The importance to understand this stochastic phenomenon is obvious.

4. A stochastic model for turbulence

Next, we report on a new approach to get an understanding of the statistics of small-scale wind fluctuations as shown, for example, in Fig. 4. In [5] it was shown that the wind fluctuations are very similar to those obtained in turbulent flows of the laboratory (ideal fully developed turbulence), if the wind field is divided into segments with different mean values of the wind speed (averages were typically done over several minutes). Thus, the wind can be considered as a mixture of turbulent wind periods with different Reynolds numbers. It seems that these segments themselves follow a fractal geometry, as becomes obvious by analyzing the duration times. The segments of nearly idealized turbulence can be described by a special stochastic process. Therefore, we consider the scale dependence of the velocity increments $u_\tau = u(t + \tau) - u(t)$. Scale dependence means the change of the wind speed fluctuation u_τ with τ. This

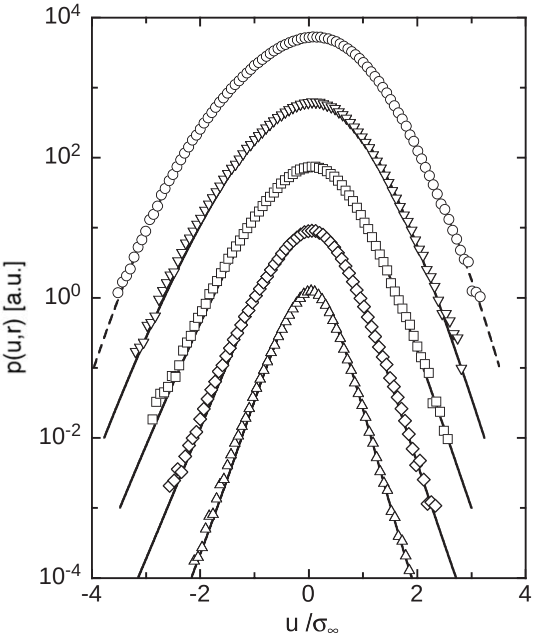

Fig. 5. Probability density functions (pdfs) $p(u,r)$ for different scales r as a function of the velocity increment u_r (open symbols), measured in a free jet. Starting from an almost Gaussian shape at the largest or integral scale (upper curve), the pdfs become more and more intermittent or heavy tailed as r decreases (lower curves). Experimental data are compared with the numerical solutions of the Fokker–Planck equation (solid lines). Curves have been shifted in the y-direction for clarity of presentation [9].

ansatz was inspired by the well-known cascade picture of turbulence, which says that large-scale fluctuations produce smaller ones, as smaller ones produce even smaller ones until the turbulent flow energy gets dissipated on smallest scales (the so-called dissipation length which is for our measured wind data in the range of some cm and smaller). Consequently, we expect an evolution of the wind speed fluctuations with the scale τ.

It is well verified that small-scale turbulence passes over a spatially fixed obstacle in a frozen way (Taylor hypotheses of frozen turbulence) that is why the turbulent flow fluctuations are usually presented as a function of spatial distances $r = \langle u \rangle \tau$, where $\langle u \rangle$ denotes the mean velocity. Here we go on with our discussion using the spatial increment notation, u_r, instead of u_τ.

The statistics of u_r is usually characterized by the moments $\langle u_r^n \rangle$ or, equivalently, by their probability density functions (pdf) $p(u_r, r)$. Those pdfs are known to show significant deviations from the Gaussian shape for small separation scales r (see Fig. 5). This phenomenon is known as intermittency and often analyzed in terms of multiscaling $\langle u_r^n \rangle \propto r^{\xi_n}$ [6].

As a new approach to characterize the pdfs $p(u_r, r)$, we consider u_r as a stochastic variable of a Markov process in r, which determines the evolution of $p(u_r, r)$ in r. This evolution is described by a generalized diffusion equation, the Fokker–Planck equation:

$$-r\frac{\partial}{\partial r}\,p(u_r,r)=\left\{-\frac{\partial}{\partial v}\,D^{(1)}(u_r,r)+\frac{\partial^2}{\partial u_r^2}\,D^{(2)}(u_r,r)\right\}p(u_r,r)\,. \tag{1}$$

The coefficients $D^{(1)}$ and $D^{(2)}$ which completely determine this equation can be estimated from experimental data via the estimation of conditional probabilities of finding u_r under the condition that on a larger scale, $r' > r$, a value $U_{r'}$ was found. From such an analysis, we find a linear dependence of $D^{(1)}(u_r,r)$ on u_r and a quadratic dependence for $D^{(2)}$:

$$D^{(1)}(u_r,r)=-\gamma(r)u_r;\quad D^{(2)}(u_r,r)=\alpha(r)-\delta(r)u_r+\beta r u_r^2\,. \tag{2}$$

By comparing the numerical solution of (1) with the pdfs determined directly from experimental data, it can be shown that a Fokker–Planck equation with coefficients given by (2) describes the measured pdfs $p(u_r,r)$ correctly, including anomalous stochastic effects (see Fig. 5). For further details on this analysis of fully developed turbulence and the implications of our results on the theory of turbulence, we refer the reader to Ref. [7–9].

To conclude, we point out that this reconstructed stochastic process for the turbulent wind data can serve as a model to generate typical wind data, see also Ref. [10].

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