

Modellierung atmosphärischer Turbulenz zur erweiterten Simulation von schwankenden Windlasten auf Solar- und Windenergieanlagen

Modeling Atmospheric Turbulence for Advanced Simulations of Unsteady Wind Loads on Solar and Wind Energy Systems

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Kurzfassung

Der dauerhafte und effiziente Betrieb von Windenergie- und Photovoltaik- (PV-) Anlagen hängt maßgeblich davon ab, inwieweit die Anlagen wechselnden Windbedingungen standhalten. Sind Schäden erst einmal vorhanden, können sie sich im Laufe der Zeit durch wechselnde Lasten und Vibrationen, die durch Turbulenz und aerodynamische Instabilitäten angeregt werden, schnell verschlimmern. Extreme und wechselnde Windlasten verlässlich zu simulieren ist daher für die Bewertung der Lebensdauer von großer Bedeutung. Die vorliegende Arbeit demonstriert, wie Windlasten auf Solar- und Windenergiesysteme mithilfe verschiedener Softwarewerkzeuge simuliert werden können. Dabei liegt der Fokus auf der Modellierung der turbulenten Windverhältnisse als Voraussetzung für die Simulation variierender Lasten.

Abstract

Durable and efficient operation of wind turbines and photovoltaic (PV) systems depends on their ability to withstand highly variable wind conditions. Once initiated, damage can worsen quickly due to reversing loads and structural vibrations, excited by unsteady winds and aerodynamic instabilities. The ability to compute such unsteady wind loads is therefore important, for pre-design, structural-health monitoring, and lifetime analysis. This paper demonstrates wind-load simulation capabilities across software tools, with applications to both solar and wind energy systems. Particular attention is paid to the modeling challenges and the representation of turbulent wind environments.

1 Introduction

Wind loads govern the lifetime and fatigue of structures and buildings. A detailed assessment, however, is rarely feasible due to limited availability of instrumented structures and computational resources. To overcome the associated design bottleneck, the long-standing paradigm in wind engineering has been to develop standardized rules for the design of structures and the wind loads associated to them based on specifically designed wind tunnel and field experiments. Relevant pioneering work can be attributed to Davenport, who introduced the concept of the wind loading chain [1] and advanced statistical descriptions on the basis of extreme value theory [2]. This approach has become established practice and has been formalized by wind loading standards and codes of practice (e. g. [3,4]). Regular updates, based on advances in research, reflect the specific needs of PV and wind energy systems.

Despite the progress made, challenges and limitations have remained with respect to unsteady loading and its consequences. PV systems (e. g. [5,6]) and wind turbines (e. g. [7,8]) are characterized by much smaller inertia than buildings and other structures due to their lightweight design in combination with a relatively large wind-exposed area and reliable loads obtained only experimentally.

Computational approaches provide an economical alternative to costly experiments, offering further insight into the air flow, load and stress distributions, which are not easily accessible to measurements. However, modeling uncertainties can be significant, computational results in conflict with measurements or codes, resulting in disagreement on design provisions (e. g. [5]). For this reason, the main objective of this work is to showcase some modeling challenges associated with aerodynamics and atmospheric turbulence, affecting unsteady wind loading of PV and wind energy systems.

The rest of this paper is organized as follows. Section 2 introduces some fundamentals of computational wind engineering. Section 3 demonstrates computational approaches for the simulation of an onshore wind turbine and a ground-mounted PV system. Last, Section 4 closes with some concluding remarks.

2 Computational Wind Engineering in Wind and Solar Energy

Computational wind engineering addresses the development and application of simulations tools that provide a software implementation of Davenport's wind loading chain by a hierarchy of numerical models. Such tools can

offer additional insight, but they are constrained by cost and fidelity. The highest fidelity is offered by computational fluid dynamics (CFD), which has predictive capabilities, but is also the most costly approach. CFD can provide detailed information based on approximate solutions to the governing conservation equations for mass, momentum, and energy (e. g. [6]). Engineering tools are less costly, but limited to lower fidelity due to utilization of reduced-order or surrogate models that rely on additional modeling assumptions (e. g. [8]). High- and low-fidelity simulation tools depend crucially on the representation of the local wind environment.

The wind environment of PV systems and wind turbines is governed by the atmospheric boundary layer (ABL) [9], which denotes the lower part of the atmosphere, up to height of about 1-2 km. The ABL exhibits characteristic wind fields that are influenced by terrain, vegetation, and surface properties (like texture and roughness), and energetically constrained by the local atmospheric conditions. Modeling of solar and wind energy systems is particularly challenged by atmospheric turbulence, which denotes the chaotic variability of atmospheric wind fields on time scales as short as seconds to minutes [11], calling for advanced modeling strategies.

3 Application Cases

3.1 Wind Turbine in Unsteady Conditions

Fast computation of unsteady wind loads benefits the development of intelligent control strategies for wind turbines in order to harmonize power generation, reduce fatigue loads, and steer wakes in wind farms (e. g. [8,12]). This requires reduced-order modeling of wind turbines, foremost rotor aerodynamics and generator torque, in response to the incoming wind of a turbulent ABL.

A representative example is given in **Figure 1**, in which a full-scale model of a DTU 10 MW wind turbine [13] is shown, computationally investigated with the aeroelastic wind turbine simulation tool QBlade [14]. The wind turbine has a hub height of 120 m and a rotor diameter of 178 m, composed of three blades. Aerodynamic forces are estimated for discrete segments of the structural beam elements based on simplifying assumptions, such as potential flow theory, and a wake model in order to represent the loss in wind speed due to wind power extraction and rotor-induced turbulence [8,14]. The structural response is visible by blade bending (**Figure 1a**), here demonstrated for a mean wind speed of 10 m/s at hub height.

Turbulent atmospheric inflow is synthesized with TurbSim [15] by spectral filtering, which is one out of a number of available methods (e. g. [16,17,18]). TurbSim generates a 3-D turbulent box by spectral filtering of random numbers. The coarse spatial resolution (10 m distance between grid points in the inflow plane) can only represent large-scale flow features, like the red-colored wind gust in the inflow plane (**Figure 1b**).

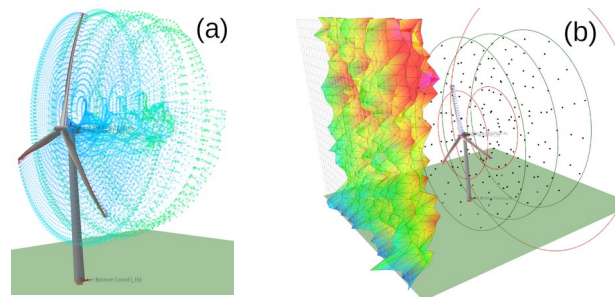


Figure 1 Dynamic simulation of a DTU 10 MW wind turbine with QBlade. (a) Snapshot showing the modeled free-vortex helical wake (blue) and blade bending. (b) Visualization of the instantaneous turbulent inflow as generated with TurbSim. Courtesy by Zubaer Haque, BTU.

A key limitation of spectral filtering approach is the construction of a “frozen-in” wind field. As suggested in [19], an alternative approach is the utilization of stochastic one-dimensional turbulence (ODT) [20], in a formulation applicable to the ABL [21,22]. ODT evolves the instantaneous wind velocity and additional scalar profiles if needed. Forcing and diffusive transport are directly resolved, whereas turbulent transport is modeled by a stochastic processes, formulated by mapping events, whose frequency depends on the locally available energy.

The modeled evolution of the instantaneous wind profile is shown in **Figure 2** for TurbSim, from the DTU 10 MW case in QBlade, and a canonical ABL case in ODT. The profiles shown represent snapshots taken at uniformly distributed output times, horizontally shifted by an arbitrary, constant offset. The profiles are normalized by the geostrophic free-stream velocity and the boundary-layer thickness, respectively. Present TurbSim results assume a parameterized reference wind profile with a hub-height velocity of 12 m/s at 120 m and a low-level jet of same speed at 100 m. Furthermore, IEC wind class Ia [23] properties are assumed, prescribing a turbulence intensity of 16%. In ODT, no feature parameterization is needed, since the solution emerges from the previously calibrated model [22] for the prescribed forcing, which is here a maintained nonzero free-stream velocity in geostrophic balance. The main difference between the two model setups is the nominally much lower wind speed in ODT to make full-scale vertical resolution numerically feasible.

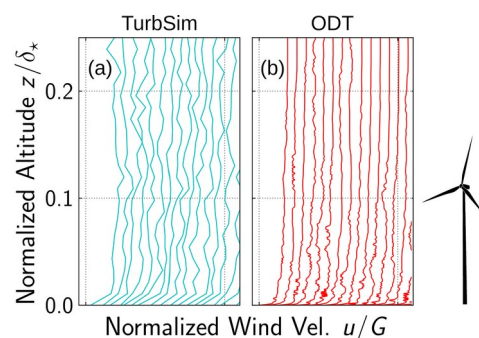


Figure 2 Instantaneous wind velocity profile evolution in (a) TurbSim (nominal $Re = 1,222,000$), and (b) stand-alone ODT ($Re = 5,000$). Profiles are normalized for comparison. A wind turbine is sketched as height reference.

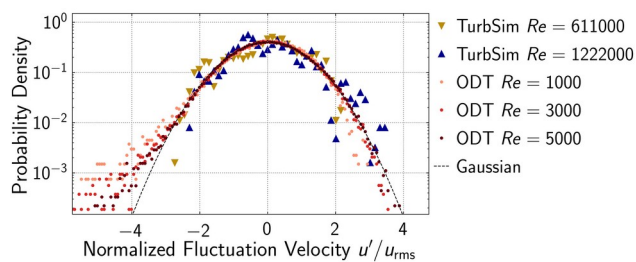


Figure 3 Probability density of the fluctuation velocity in the ABL. TurbSim cases correspond to a hub-height velocity of 6 m/s and 12 m/s, respectively. ODT simulations for various wind speeds at a lower magnitude regime exhibit saturation of non-Gaussian tails, indicating that wind gusts affect statistics beyond three standard deviations.

The velocity intermittency is shown in **Figure 3**, extending [19]. The fluctuation velocity is obtained from local time series and normalized by the standard deviation of the corresponding data record. The upside-down parabola in the semi-logarithmic axes represents a Gaussian normal distribution. Turbulent flows are intermittent and expected to deviate from the normal distribution, foremost in the tails (e. g. [18]). This property is reproduced by ODT for the turbulence-dominated region of the ABL. This holds even for fairly low wind speeds characterized by low Reynolds numbers (Re). Fluctuations in TurbSim are almost Gaussian, notably underestimating extreme wind gusts.

3.2 Unsteady Wind Loads on a PV System

Ground-mounted PV systems have a typical height of only a few meters and are hence located in the atmospheric surface layer [9]. The turbulence intensity increases nonlinearly towards the ground whereas the mean wind speed decreases (e. g. [1,2]). Turbulent wind gusts in the vicinity of the surface govern the unsteady wind loads, and the fatigue of panels and the mounting system. The low height of PV systems poses a challenge for wind tunnel measurements of such loads since the smaller scale models cannot be easily measured [24], rendering full-scale field measurements crucial. This challenge can be addressed computationally by high-fidelity CFD models, like the single-purpose CFD software PVade [25] and the multi-purpose CFD-library OpenFOAM [26]. In order to cut computational cost, a preliminary model comparison is performed for a minimalistic case with reduced computational burden by relaxing CFD best practice guidelines. The minimalistic domain and configuration of the PV system investigated is given in **Figure 4**, showing a dual-axis solar tracker represented by a single square panel with 8 m edge length and a thickness of about 0.1 m. The mean velocity profile of the incoming wind, parameterized by a power law [2], is sketched on the left, at the inflow boundary of the flow domain. This profile is used to initialize the flow. Only the bottom boundary and PV panel are treated as no-slip boundaries. Top, front and back are free-slip, the left side inflow, and the right side outflow boundary conditions. Further details are given in [25].

An exemplary CFD solution obtained with PVade for low-wind conditions is shown in **Figure 5**. The central

vertical slice shows the spatial distribution of the instantaneous velocity magnitude by blue-red pseudocolors after the initial transient as passed. The airflow separates at the panel edges and develops a turbulent wake downstream. The visible front half of the panel's sun-facing side visualizes the distribution of the instantaneous fluid stress that acts on the PV panel by another set of pseudocolors. Last, simulated time series of the lift coefficient are shown in **Figure 6** for PVade and OpenFOAM. The two CFD solvers differ by their discretization schemes and subgrid-scale turbulence models, utilizing the Smagorinsky (Smag.) and the wall-adapting local eddy-viscosity (WALE) model. The initial transient is similar, but the saturation is different. OpenFOAM is generally more dissipative than PVade, damping down wind fluctuations and unsteady lift forces emerging due to vortex shedding.

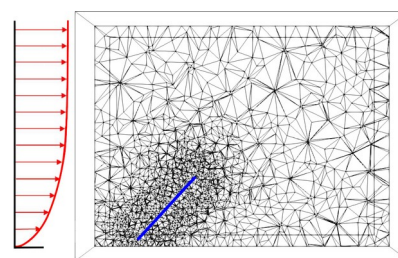


Figure 4 Unstructured mesh (black) of the flow domain around a ground-mounted square PV panel (blue) with an edge length of 8 m without mounting system. The incoming wind profile (red) is sketched and obeys a power law.

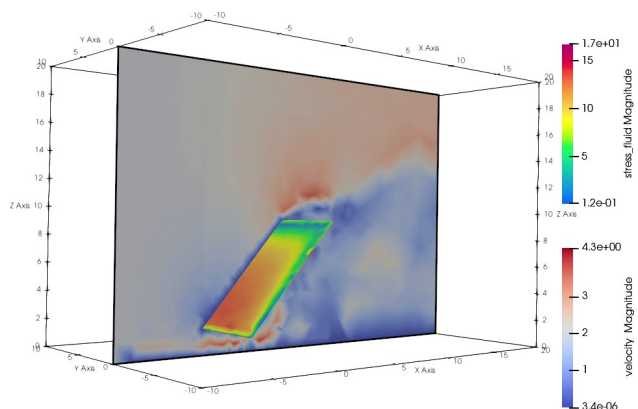


Figure 5 Visualization of the instantaneous wind field (blue-red) around a square PV system together with the wind stress (rainbow colors) obtained by a CFD simulation with PVade. Courtesy by Joseph Gerardi, BTU.

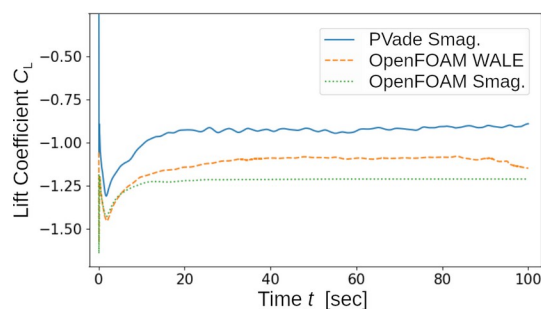


Figure 6 Simulated lift coefficient for a square PV panel varying the CFD solver and turbulence model. Courtesy by Hemanth N. Kotra, BTU.

4 Concluding Remarks

Numerical simulation of unsteady wind loads on PV and wind energy systems requires dynamical models capable of representing aerodynamic and turbulent flow features across scales and model fidelity. This is particularly the case for turbulent atmospheric boundary layers. Map-based stochastic modeling can serve as gap-bridging approach, addressing both cost and physical compatibility.

5 Acknowledgment

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