

# Comparison of the Development of a Wind Turbine Wake Under Different Inflow Conditions

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**Abstract** We present a wind tunnel study of a model wind turbine wake with regard to different inflow conditions. The aim is to examine the influence of intermittent flows on the wake. For this, a regular grid that produces non-intermittent inflow and an active grid that creates intermittent inflows have been used. As a reference case, also laminar inflow conditions were examined. The development of the centerline turbulence intensity and mean velocity with increasing distance from the wind turbine was investigated, and an influence of the different characteristic features of turbulence on the wake recovery was found. The results expand and partially contradict previous results.

## 1 Introduction

Turbulence is shown to have a major influence on the wind energy conversion process. As wind energy converters are usually built in wind farms, not only the atmospheric turbulence influences the machines, but also the turbulence that develops behind the wind energy converters. To optimize the wind farm layout and to design wind energy converters according to the surrounding conditions, profound knowledge of the wind turbine wake and its development is important. A first step towards a proper description is to scrutinize the development of the velocity mean  $\bar{v}$  and the standard deviation  $\sigma_v$ , which has already been done in several CFD, laboratory and field studies. Here, a study based on wind tunnel experiments is presented, where the focus is on the examination of the influence of different turbulent inflows on the development of the wake of a load-controlled model wind turbine.

In the past, several laboratory studies of wakes of model wind turbines exposed to turbulent inflow conditions have been carried out. In [1], the wake of a model wind turbine in two different turbulent boundary layers is examined, namely, the influence of a rough and a smooth boundary layer on different quantities in the wind

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turbine wake at various downwind positions are compared, and wake profiles are studied. They conclude that the inflow turbulence is beneficial for the recovery of the velocity deficit in the wake (in the following called wake recovery). In comparable studies like e.g. [2], the effect that turbulent inflow leads to a faster wake recovery is confirmed.

Above-mentioned studies come to the general conclusion that the inflow turbulence has an influence on the wake. However, in many studies, including [1, 2], the inflow turbulence is only specified by mean value and standard deviation. Consequently, the intermittency, which is one important feature of the atmospheric wind (cf. [8]) and which could be related to an increased wind turbine failure rate [7], is often not accounted for in the layout and discussion of experiments. The term intermittency refers to the gustiness of a flow, and it can be characterized by the probability density function (PDF)  $p(\delta v(\tau))$  of velocity increments  $\delta v(\tau) = v(t + \tau) - v(t)$ . This description takes into account the velocity fluctuations over a time lag  $\tau$ . Here, it should be pointed out that the time lag  $\tau$  or, respectively, the corresponding spatial scale obtained by the use of Taylor's hypothesis of frozen turbulence, plays an important role for the wake structure if these scales are within those that determine the wake structure, i.e. the size of the rotor or the size of the chord of the blades.

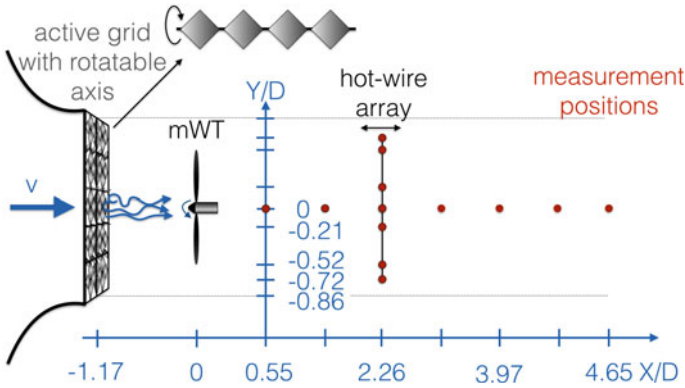
The aim of this paper is to examine the influence of intermittency on the wake. For this, the impact of two fundamentally different turbulent inflows, one with intermittent and one with non-intermittent features on the relevant scales, is examined experimentally. In Sect. 2, the experimental setup is presented. Section 3 shows the results which are directly discussed. Finally, in Sect. 4, a conclusion closes this article.

## 2 Experimental Setup

The setup is presented in Fig. 1. A model wind turbine with rotor diameter  $D = 58$  cm and tip speed ratio  $\lambda = 7.2$  is installed in a closed-loop wind tunnel with open test-section [6]. The measurements of the wake are carried out with seven hot-wire probes aligned in an array that is traversed along the centerline up to a distance of  $X/D = 4.65$ . The sampling frequency is  $f_s = 20$  kHz, and a low-pass filter with a cut-off frequency of 10 kHz is used.

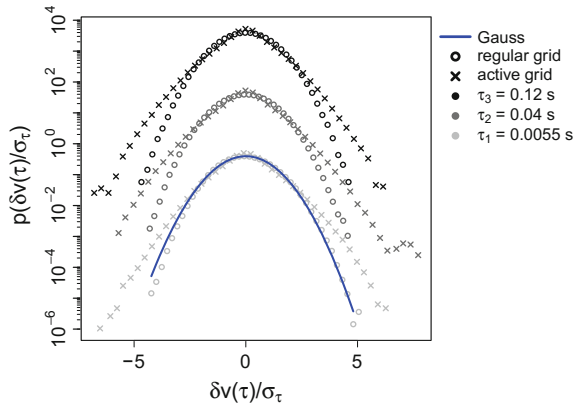
To create the above-mentioned different turbulent inflows, a regular and an active grid are used. The regular grid (mesh size of 4.4 cm) creates on the scales of the rotor non-intermittent, i.e. Gaussian, turbulence, while the active grid is capable of creating respective intermittent flows (cf. e.g. [8]): Several vertical and horizontal axes with diamond-shaped flaps can be rotated, and a motion pattern of all axes allows to create customized turbulent flows [3]. In this experiment, we use a motion protocol that recreates typical statistical characteristics of free field wind data, rescaled to wind tunnel dimensions. As a third reference case, a quite laminar inflow is used.

For the two turbulent inflow conditions, the PDFs of velocity increments are plotted in Fig. 2 for different time lags  $\tau$ . The PDFs are normalized to the standard deviations of the increment time series,  $\sigma_\tau$ , and they are shifted vertically for clarity.



**Fig. 1** Top-view of the setup: The model wind turbine is placed in different turbulent flows created by a regular and an active grid. The wind tunnel with outlet ( $80 \times 100$ )  $\text{cm}^2$  is operated with an open test section. A hot-wire array with seven probes is used to traverse the centerline of the wake

**Fig. 2** PDF of velocity increments for different time lags  $\tau$ .  $\tau = 0.0055$  s corresponds to the chord length at approximately 50% of the radius,  $\tau = 0.04$  s corresponds to the rotor radius and  $\tau = 0.12$  s corresponds to  $1.5 D$ . The PDFs are shifted vertically for clarity



The standard deviations of the active grid  $\sigma_{\tau,act}$  are for the chosen  $\tau$  twice the value of the regular grid's standard deviations  $\sigma_{\tau,reg}$ . The corresponding spatial scales are chosen to match the turbine geometries:  $1.5 D$  corresponds to  $\tau = 0.12$  s  $\approx 0.87$  m,  $0.5 D$  corresponds to  $\tau = 0.04$  s  $\approx 0.28$  m and the chord length at approximately 50% of the radius corresponds to  $\tau = 0.0055$  s  $\approx 0.04$  m. It can clearly be seen that the regular grid produces Gaussian statistics, whereas the active grid creates intermittent statistics on our selected scales.

The mean inflow velocities and turbulence intensities  $TI = \sigma/\bar{v}$  of the free inflows (i.e. without turbine) at rotor position are presented in Table 1. The values are averaged over all seven sensors. In the following, the velocities are used as reference and normalization inflow velocities. As the mean wind speeds are set by a constant wind tunnel motor control voltage, the inflow velocity varies for the different inflow conditions.

**Table 1** Mean averaged velocities  $\bar{v}_0$  and turbulence intensities  $TI_0 = \sigma_0/\bar{v}_0$  of the different inflow conditions at rotor position (no turbine, thus the index 0)

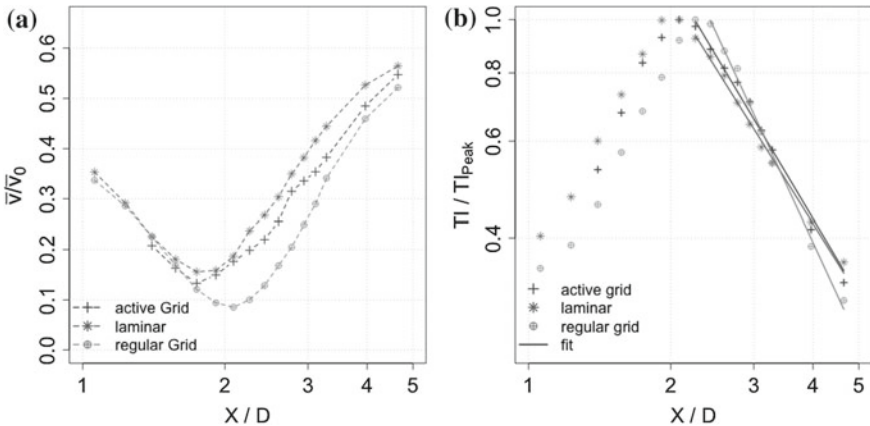
	Laminar	Regular grid	Active grid
$\bar{v}_0/\text{m/s}$	7.56	7.28	8.07
$TI_0/\%$	1.36	6.72	12.81

### 3 Results and Discussion

In the following, the downstream evolution of the normalized mean velocity  $\bar{v}/\bar{v}_0$  and turbulence intensity  $TI/TI_{peak}$  in the wake are shown and discussed with regard to the inflow conditions (cf. Fig. 3a, b).

The mean velocity drops as expected due to the pressure gradient caused by the turbine. At  $X/D \approx 2$ , the wake recovery starts. An influence of the inflow turbulence is visible: In case of the laminar and the intermittent inflow, the maximum wake deficit and the recovery are comparable. The maximum wake deficit in case of the non-intermittent inflow is significantly higher, but the wake recovery appears to be faster, although  $TI_{0,reg}$  is roughly half of  $TI_{0,act}$ . Therefore, contradictory to other studies, we find that a higher turbulence degree in the inflow conditions does not necessarily lead to a faster recovery of the mean wind speed. The statistic characteristics of the inflow turbulence on turbine-related scales seem to play an additional role in the wake development.

In Fig. 3b, the development of the turbulence intensity over  $X/D$  is shown. Inspired by [4], the turbulence intensity is normalized to the respective peak turbulence



**Fig. 3** Development of the wind turbine wake's normalized mean velocity (a) and to the peak turbulence intensity normalized turbulence intensity (b) for different inflow conditions. The quantities are plotted logarithmically over  $X/D$ . The turbulence intensity is displayed in a log-log plot and a power law  $TI/TI_{peak} = \alpha \cdot (X/D)^{-\beta}$  is fitted

**Table 2** Fit parameters of the TI's power law fit  $TI/TI_{Peak} = \alpha \cdot (X/D)^{-\beta}$

	Laminar	Regular grid	Active grid
$\alpha \pm \Delta\alpha$	$2.87 \pm 0.12$	$5.21 \pm 0.38$	$3.23 \pm 0.20$
$\beta \pm \Delta\beta$	$1.37 \pm 0.04$	$1.87 \pm 0.07$	$1.45 \pm 0.07$
$\chi^2_{PL}$	0.00015	0.00028	0.00037

intensity  $TI_{Peak}$  in an attempt to collapse the curves. It can be seen that the turbulence intensity peaks around  $X/D \approx 2$  and then decays. As publications as [5] have shown a power law decay of the velocity deficit, which is directly linked to the turbulence intensity, a power law  $TI/TI_{Peak} = \alpha \cdot (X/D)^{-\beta}$  was fitted to the decay region. The fit parameters and the mean square residuals  $\chi^2$  can be found in Table 2. The low values of  $\chi^2$  indicate that the power law fit shows a good agreement.

To our knowledge, we are the first ones to connect the turbulence decay to classical wake decay description methods and to investigate also the evolution of the turbulence intensity. In analogy to the behavior of the mean velocity,  $\beta$  is similar in case of the laminar and the intermittent inflow, but differs in case of non-intermittent inflow. As a consequence of the higher decay exponent, in case of the non-intermittent inflow, the turbulence intensity decays faster, and thus the decay curve even crosses the other curves. This indicates that the intermittent turbulence counteracts the beneficial faster turbulence decay in case of Gaussian inflow turbulence.

## 4 Summary and Conclusion

We presented a study of the influence of different inflow conditions on the development of a wind turbine wake. Hot-wire measurements have been carried out at different positions along the streamwise axis up to  $X/D = 4.65$ .

The evolution of the mean velocity at centerline is shown to be dependent on the statistical characteristics of the inflow turbulence. While the wake recovers similarly for laminar and intermittent inflow conditions, the wake recovery in case of non-intermittent turbulence is faster, although the inflow turbulence was significantly lower compared to the intermittent case.

The decay of the turbulence intensity can be approximated by a power law fit after peaking around  $X/D \approx 2$ . Similar to the mean velocity, the inflow conditions also affect the turbulence decay. The turbulence intensity decays faster in case of non-intermittent inflow although having the lower inflow turbulence degree.

Both analyses suggest that on turbine scales intermittent turbulence counteracts the recovery of the mean velocity and the decay of the turbulence intensity. Whether this trend is conserved at larger distances  $X/D$  has to be further examined.

In conclusion, an influence of different characteristic features of the inflow turbulence on the wake of a model wind turbine could be shown. Therefore, a description

of the inflow with mean velocity and turbulence intensity is not sufficient, and experiments in turbulent inflows have to be designed carefully to gain profound knowledge in cases of turbulence generation in turbulent surroundings.

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