

Effect of inflow conditions on tip vortex breakdown in a high Reynolds number wind turbine wakeMano Grunwald *Max Planck Institute for Dynamics and Self-Organization, 37077 Göttingen, Germany
and Department of Physics, Georg-August-Universität Göttingen, 37077 Göttingen, Germany*Claudia E. Brunner **Max Planck Institute for Dynamics and Self-Organization, 37077 Göttingen, Germany*

(Received 7 March 2025; accepted 22 October 2025; published 27 January 2026)

Understanding the re-energization of wind turbine wakes is crucial for the design and control of wind farms. Close to the rotor, this process is determined by the dynamics of the tip vortices. Here, we experimentally investigate the downstream evolution of the tip vortices for different inflow conditions. The experiments were performed in the Variable Density Turbulence Tunnel at the Max Planck Institute for Dynamics and Self-Organization, which uses pressurized SF₆ as the working fluid to achieve a turbine diameter-based Reynolds number of $Re_D = 2.9 \times 10^6$. An active turbulence grid was used to generate atmospheric inflow conditions with varying levels of mean shear and turbulence intensity. Hot wire measurements of the streamwise velocity component were conducted in the inflow and the wake of a model wind turbine MoWiTO 0.6 for various tip speed ratios and are used to investigate the scaling of tip vortex breakdown in the near wake. Three different scaling regimes can be identified, which we link to an initial advection phase, the vortex breakdown, and a decaying turbulence regime. While the scaling in the vortex breakdown regime is only weakly affected by variations in mean velocity shear and turbulence intensity, higher tip speed ratios lead to faster breakdown.

DOI: [10.1103/PhysRevFluids.11.014608](https://doi.org/10.1103/PhysRevFluids.11.014608)**I. INTRODUCTION**

Wind energy is a key technology in the transition to green energy production. Wind turbines are commonly organized in wind farms, where multiple turbines operate in close proximity. This leads to interactions between the turbines, with downstream turbines experiencing the wakes of upstream turbines as their inflow. These interactions reduce the generated power [1,2] and increase fatigue loads on the blades of the turbines [3]. Therefore, wakes play a critical role in the development of wind farm layouts, necessitating a comprehensive understanding of their dynamics.

Wind turbine wakes are dominated by coherent structures: vortices are shed from the roots and tips of the rotor blades and transported downstream. Due to the circular motion of the rotor, helical vortex tubes are formed. While the root vortices break down close to the rotor, the tip vortices can persist several rotor diameters downstream. It is their evolution that primarily determines the initial

*Contact author: claudia.brunner@ds.mpg.de

dynamics of the wake [4–6]. In the near wake, the velocity is low as the wind turbine removes kinetic energy from the flow. Only once the tip vortices break down does the wake begin to re-energize [7,8]. Mechanisms of tip vortex breakdown have been studied extensively in the literature and can be grouped into two categories: interactions with adjacent vortices and interactions with surrounding turbulence. Which mechanisms dominate is likely dependent on the exact flow conditions. As such, understanding what mechanisms induce vortex breakdown under realistic atmospheric conditions and what scaling laws they follow is of great interest to the wind energy community.

Breakdown due to interactions with adjacent vortices is the most widely studied mechanism. Ivanell *et al.* [9] conducted large eddy simulations to investigate the stability of the tip vortices by perturbing them in the axial direction. They found that tip vortex breakdown is faster if subsequent helices are perturbed in different directions. This brings the vortices closer together, which promotes interactions between them. While the interaction of vortex pairs has been extensively studied at a fundamental level (see, e.g., [10]), Posa *et al.* [11] later described the breakdown mechanism of tip vortices in wind turbine wakes due to interaction in detail. After short-wave instabilities are triggered, long-wave instabilities lead to mutual induction between subsequent vortices. This eventually results in leapfrogging and the breakdown of the tip vortices into smaller eddies.

The spacing of adjacent vortices is related to the tip speed ratio (TSR):

$$\text{TSR} = \frac{\pi D f_{\text{rot}}}{\bar{u}}. \quad (1)$$

Here, D is the rotor diameter, f_{rot} is the rotation frequency of the rotor, and $\bar{u}$ is the mean velocity of the flow. The rotation rate of the rotor determines how often vortices are created at a given location, while the mean velocity determines how quickly they are advected downstream. As such, higher tip speed ratios result in closer vortices. Hu *et al.* [12] point to a decrease in tip vortex strength with increasing tip speed ratio due to the decreasing effective angle of attack of the blades. As a result, they report faster vortex breakdown at higher tip speed ratios. Thus, higher tip speed ratios not only enhance the breakdown process by decreasing the distance between vortices, but also by changing the effective angle of attack. They also record the maximum vorticity of the tip vortices as a function of downstream distance from the rotor. Interestingly, they find that the decrease in vorticity follows a power law.

In the presence of turbulence, the interaction of tip vortices with the surrounding flow is also thought to induce vortex breakdown. Ghimire and Bailey [13] found that higher turbulence intensity in the inflow leads to a faster breakdown of the tip vortices. In a subsequent study, they showed that a turbulent inflow led to fluctuations in the vortex core circulation, which were absent under laminar inflow conditions [14]. They found that these fluctuations correspond to the formation of secondary vortex structures around the tip vortices. Interactions with these structures then led to a breakdown of the tip vortices.

In the context of wind turbines, the turbulence intensity TI is typically used to characterize the inflow turbulence:

$$\text{TI} = \frac{u'_{\text{rms}}}{\bar{u}}. \quad (2)$$

Here, u'_{rms} is the root-mean-square value of the velocity fluctuations in the streamwise direction u' . Gambuzza and Ganapathisubramani [15] showed that higher turbulence intensities lead to faster wake recovery. Van der Deijl *et al.* [16] found that this effect is stronger than the effect of tip speed ratio. Yen *et al.* [17] explicitly studied the leapfrogging effect by shortening one of the rotor blades. Although this did lead to enhanced interactions between the tip vortices at low TI, interactions with the surrounding turbulence dominated vortex breakdown at higher TI.

The inflow experienced by real wind turbines is typically not only turbulent, but also sheared. Chamorro and Porté-Agel [18] show that the mean velocity profile of the wake can be understood as a superposition of the mean inflow profile and a wake in uniform inflow conditions. Li *et al.* [19] confirm this using an active turbulence grid to create sheared inflow conditions. However, few

studies have investigated the impact of shear on tip vortex breakdown. Parinam *et al.* [20] conducted a large eddy simulation of a wake in a sheared laminar inflow and observed a tilting of the helical tip vortex structures due to the shear. This led to differences in the spacing of adjacent vortices: at the bottom of the rotor, tip vortices were closer together and thus interacted sooner, leading to faster breakdown, while at the top of the rotor, they were spaced farther apart, delaying interactions and breakdown.

Because vortex breakdown is sensitive to the local flow conditions, it is crucial to investigate these effects under conditions that are as realistic as possible. However, the Reynolds numbers of wind turbine flows are exceptionally high and therefore challenging to recreate in numerical studies and laboratory experiments. The turbine-based Reynolds number $Re_D = \bar{u}D/\nu$ is typically on the order of $10^6 \lesssim Re_D \lesssim 10^8$. Here, ν is the kinematic viscosity of the fluid. However, most laboratory experiments of wind turbine wakes have been conducted at Reynolds numbers that are more than two orders of magnitude lower than those of full-scale wind turbines. An exception to this is the use of pressurized wind tunnels, which generate high Reynolds number flows by lowering the kinematic viscosity. Piqu   *et al.* [21] conducted hot wire measurements in such a facility to study the wake of a model wind turbine and observed a Reynolds number invariance of the wake velocity field over $2.7 \times 10^6 \leq Re_D \leq 7.2 \times 10^6$. In a subsequent study, they investigated coherent structures in the wake by associating them with the presence of distinct peaks in the velocity spectra [22]. The peak corresponding to the tip vortices decreased with increasing downstream position. Importantly, while these experiments achieved full-scale Re_D , they were conducted under laminar inflow conditions, so that the effect of inflow turbulence could not be studied.

Here, we present an experimental investigation of tip vortex breakdown in turbulent, sheared flows at full-scale Reynolds numbers. These experiments were conducted in the Variable Density Turbulence Tunnel (VDTT) at the Max Planck Institute for Dynamics and Self-Organization to achieve a Reynolds number of $Re_D = 2.9 \times 10^6$. An active turbulence grid was used to control mean velocity shear and turbulence intensity in the inflow. To the authors' knowledge, this is the first laboratory study of a wind turbine in a high Reynolds number ($Re_D \sim 10^6$) turbulent flow. The focus of the present study is not to identify which specific mechanisms initiate vortex breakdown, but rather the scaling of the breakdown process in turbulent shear flows. As such, we present the effects of turbulence intensity, mean shear, and tip speed ratio on the signatures of the tip vortices in the velocity spectra.

II. METHODOLOGY

A. Variable density turbulence tunnel

The experiment was conducted in the Variable Density Turbulence Tunnel (VDTT) at the Max Planck Institute for Dynamics and Self-Organization in G  ttingen. The VDTT, shown in Fig. 1, is a closed-loop wind tunnel in an upright position. It is 18.2 m long, 5.3 m tall, and contains an upper and a lower measurement section. The present experiments were conducted in the 8.8 m long upper measurement section. The VDTT is specifically designed to investigate high-Reynolds-number flows. To this end, sulfur hexafluoride (SF_6) at up to 15 bar is used as the working fluid due to its low kinematic viscosity. A 210 kW fan located at the downstream end of the lower measurement section is used to circulate the gas at up to 5 m/s. The experimental conditions of the present study are shown in Table I. Before the working fluid enters the upper measurement section, it passes through a heat exchanger to ensure constant temperature throughout the experiment. The heat exchanger additionally acts as a flow straightener that removes any fan rotation from the flow. Downstream of the heat exchanger, three meshes with decreasing mesh sizes are installed to laminarize the flow. The wind tunnel is described in detail in Bodenschatz *et al.* [23].

The experimental setup is shown in Fig. 2. An active turbulence grid is located immediately downstream of the laminarizing meshes. A customary inflow profile is generated with the active grid, and the streamwise velocity component of the flow is recorded at a variety of locations

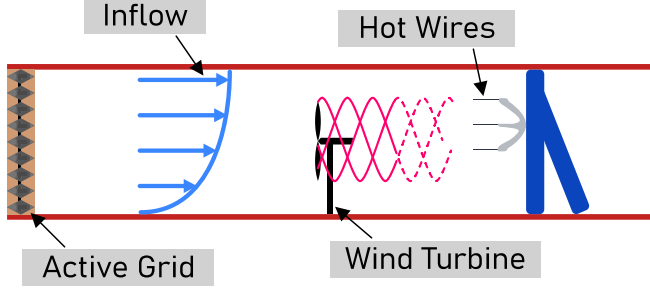


FIG. 2. Experimental setup in the upper measurement section of the VDTT.

correlation is introduced following the principles described in Griffin *et al.* [30]:

$$\phi'_{ij} = \sum_{k=1}^3 \sum_{l=1}^3 \Omega_{kl} \phi'_{i+k-2, j+l-2}. \quad (4)$$

Here, a 3×3 convolution with a convolution kernel $\Omega_{kl} = 1/9$ is used. At the boundaries, reflective boundary conditions are employed such that $\phi'_{(-1)j} = \phi'_{1j}$ and $\phi'_{i(-1)} = \phi'_{i1}$. Using this kernel, the angle of each flap is determined by the average of its own angle and the angles of its eight neighboring flaps.

Target velocity profiles with varying levels of shear and turbulence intensity were determined. The parameters of the above grid motion protocol were then iteratively adjusted until satisfactory agreement between the resulting flow and the target profiles was achieved. As the target mean velocity shear is in the vertical direction, the mean flap angles are considered to be the same across each row, such that $\bar{\phi}_{ij} = \bar{\phi}_i$. The optimization parameters were the mean angle of each row $\bar{\phi}_i$, D_{ou} and the wind tunnel fan speed. The parameters used for the final grid protocols are presented in the Supplemental Material [32]. More details on the active grid are provided in Bodenschatz *et al.* [23] and Griffin *et al.* [30].

C. Model wind turbine

The wind turbine used in these experiments is a model wind turbine, MoWiTO 0.6, developed at the University of Oldenburg [33,34]. The turbine is placed 40.7M downstream of the active grid. It has a rotor diameter of $D = 0.58$ m and a hub height of $z_{hub} = 0.52$ m. The conditions shown in Table I result in a turbine Reynolds number of $Re_D = 2.9 \times 10^6$. The blade design is based on the SD 7003 airfoil. The turbine features a pitching mechanism, allowing for the simultaneous adjustment of the pitch of the rotor blades. The rotor is connected to a DC motor that acts as a generator. The turbine rotation rate is controlled by a field-effect transistor (FET), which dissipates the generated power. The voltage of the FET is adjusted using a PID controller. The increased power density of the flow in SF₆ compared to air means that at a given rotation rate, the rotor extracts more power. At high pressures, this power exceeded the maximum power the generator could convert at this rotation rate. As a result, it was not possible to apply the load necessary to fix the rotation rate, and the rotor would spin up. A gearbox with a ratio of 1 : 4.8 was installed to reduce the rotation rate of the generator and thus increase its torque. This shifted the operating conditions closer to the optimal range for this generator, so that it was able to extract the necessary power.

D. Data acquisition and post-processing

All velocity information in this study is based on streamwise velocity measurements conducted using Dantec Dynamics 55P11 hot wire probes. The probes are 1.25 mm long with a diameter of 5 μ m. The hot wires were operated in CTA mode and controlled via a Dantec Dynamics StreamLine

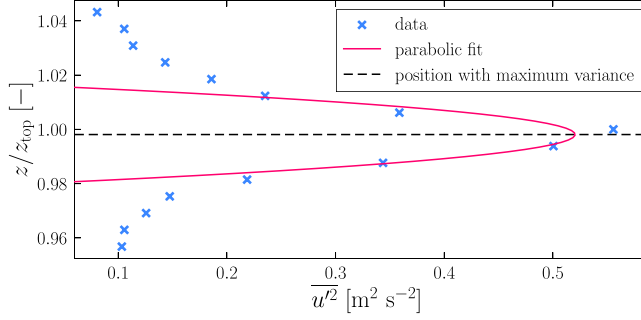


FIG. 3. Streamwise velocity variance profile at the top of the wake at $x/D = 0.25$ downstream of the rotor. The maximum of the parabolic fit is taken to be the tip vortex height, at which a longer measurement is then conducted to determine the streamwise velocity spectrum.

90N10 Frame with 90C10 CTA modules using the Dantec Dynamics StreamWare Pro v6.00 software. The overheat ratio was set to 0.8. For the connection to the modules, 20-m-long RG223 cables were used. The signal was sampled at 60.06 kHz, low-pass filtered at 30 kHz, and read out via a National Instruments PCI-6123 DAQ card. The hot wires were calibrated using pitot tubes connected to a Siemens SITRANS PDS III differential pressure transducer. Turbine data, such as the rotation rate, were sampled at 5 kHz by a National Instruments cRIO-9074 data acquisition system.

The inflow profiles are characterized at the position of the model wind turbine in the lateral center of the wind tunnel with a vertical spacing of 24 mm between measurement points. The measurements extend beyond the swept area of the rotor as shown in Fig. 4. At each measurement point, the flow is sampled for 5 min to ensure convergence of second moments. To verify convergence, 15 min measurements are conducted in the lateral and vertical center of the wind tunnel for each grid protocol.

To observe the tip vortex evolution in the wake, measurements were conducted at the lateral center of the tunnel at streamwise positions $0.25 \leq x/D \leq 6.79$ downstream of the model wind turbine. Due to wake expansion, the vertical location of the tip vortices is a function of downstream position [35,36]. To account for this, the vertical profile of the velocity variance was measured throughout the expected region following [21]. An example of such a variance profile is shown in Fig. 3. A parabola is fit to this profile, and its maximum is taken to be the tip vortex height. The flow was sampled at this position for 15 min resulting in the streamwise velocity spectra presented in Sec. III. In the two most downstream positions, the tip vortices had typically broken down so much that the variance profiles no longer showed clear maxima. In these cases, the height of the closest upstream measurement point was used.

The streamwise velocity spectra are computed using Welch’s algorithm [37] and smoothed with a moving average filter. This procedure is parametrized by the number of segments used in Welch’s algorithm and the width of the moving average window. Here, eight segments are used, while the width of the moving average window is 0.3 Hz. Details on these parameter choices can be found in the Supplemental Material [32]. Typically, turbulent velocity spectra follow a $-5/3$ scaling in the inertial range. In the inflows generated here, this scaling extends over three decades, which is indicative of a high Reynolds number flow.

E. Inflow characteristics

In a vertically sheared flow, many relevant parameters inherently vary as a function of height. This required us to select a reference height at which to define target inflow characteristics. We decided to focus on the tip vortices shed from the upper edge of the rotor because these are easiest to locate and least affected by the turbine tower. As such, the upper edge of the rotor was chosen

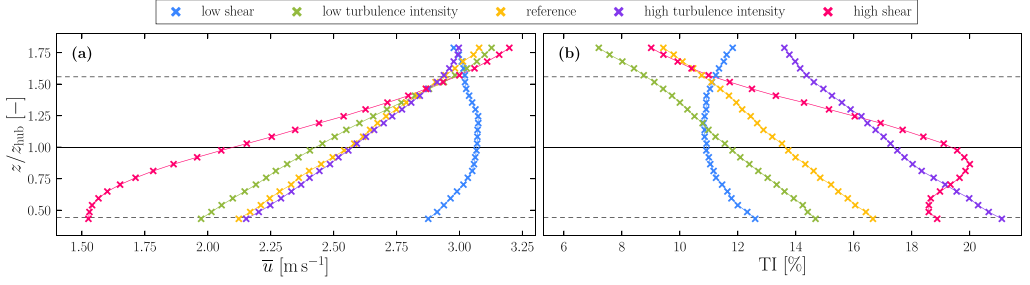


FIG. 4. (a) Mean velocity and (b) turbulence intensity profiles in the inflow. The solid black line marks the hub height of the model wind turbine, while the dashed black lines show the rotor-swept area.

as the reference location for defining the inflow conditions, rather than the hub height. To minimize Re_D effects on the tip vortices, the target mean velocity at the top of the rotor is the same for all cases. Due to the presence of boundary layers at the tunnel walls, maintaining a linear mean velocity gradient across the entire vertical profile is not possible. However, we expect the behavior of the tip vortices to be primarily sensitive to the velocity gradient across the rotor area. As such, the mean shear is defined here as the mean velocity difference $\Delta \bar{u}_D$ across the vertical span of the rotor normalized by the mean velocity at the upper edge of the rotor:

$$\frac{\Delta \bar{u}_D}{\bar{u}_{top}} = \frac{D}{\bar{u}_{top} m}. \quad (5)$$

Here, m is the slope of a linear fit to the recorded mean velocity profiles over the vertical span of the rotor, and $\bar{u}_{top}$ is the mean velocity at the upper edge of the rotor. Because turbulence in the inflow is generated not only by the active grid but also by the mean velocity shear, it is practically impossible to keep the turbulence intensity constant across the vertical profile of the test section. However, we expect the behavior of the tip vortices at the upper edge of the rotor to be primarily sensitive to the turbulence intensity at their height. As such, the turbulence intensity is referenced at the height of the upper edge of the rotor $TI_{top} = (u'_{rms})_{top} / \bar{u}_{top}$. Equivalently, the tip speed ratio is defined based on the velocity at the top of the rotor $TSR_{top} = \pi D f_{rot} / \bar{u}_{top}$.

The resulting mean velocity and turbulence intensity profiles for the five investigated inflow conditions are shown in Fig. 4, and the relevant parameters are listed in Table II. The profiles are smoothed with a moving average filter. The case of medium shear and medium turbulence intensity serves as a reference case. Two cases differ in their turbulence intensity but have approximately the same mean shear across the rotor plane, while the two remaining cases have varying mean shear but approximately the same turbulence intensity at the top edge of the rotor. As such, these five

TABLE II. Mean shear $\Delta \bar{u}_D / \bar{u}_{top}$, turbulence intensity TI_{top} , tip speed ratio TSR_{top} , integral length scale L_{11} , Kolmogorov scale η , and Taylor scale Reynolds number Re_λ for all generated inflow cases. All values are measured at the height of the upper edge of the rotor.

ID	$\Delta \bar{u}_D / \bar{u}_{top}$ [—]	TI_{top} [%]	TSR_{top} [—]	L_{11} [m]	η [μ m]	Re_λ [—]
low shear	0.13	11.3	6.0	0.53	40	1970
low turbulence intensity	0.33	8.8	6.1	1.1	51	1950
low tip speed ratio	0.27	10.8	4.1	0.88	49	2530
reference case	0.27	10.8	6.1	0.88	49	2530
high tip speed ratio	0.27	10.8	8.2	0.88	49	2530
high turbulence intensity	0.25	14.4	6.1	0.57	36	2550
high shear	0.54	11.2	6.0	0.61	43	2140

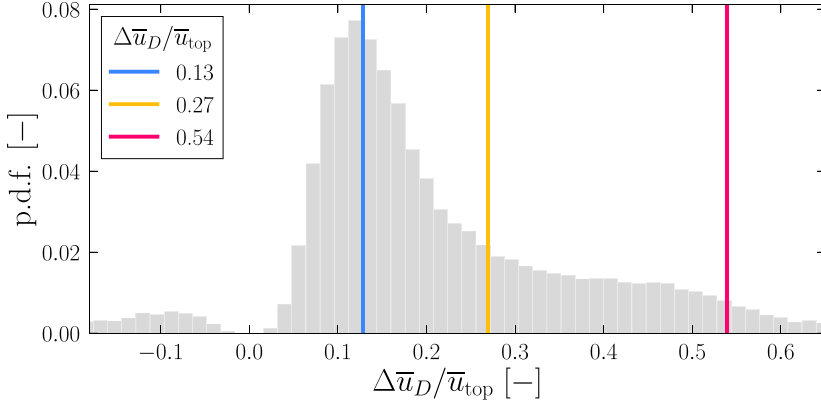


FIG. 5. Histogram of the shear conditions obtained from data recorded at the offshore measurement platform FINO3 in 2024 according to Eq. (5), assuming a rotor diameter of 150 m and a hub height of 100 m.

inflow conditions allow us to study the effects of shear and turbulence on tip vortex breakdown independently of one another. The effect of tip speed ratio was investigated using the reference case inflow condition and varying the tip speed ratio over $\text{TSR}_{\text{top}} = [4.1, 6.1, 8.2]$. The selected parameter space for shear, turbulence intensity, and tip speed ratio falls within the realistic operating conditions of wind turbines, with the turbulence intensity being on the higher end of the range. Figure 5 shows the histogram of mean shear conditions recorded at the FINO3 measurement mast in the German North Sea throughout 2024 [38], along with the shear conditions generated in this study. Evidently, these three cases cover much of the observed range of shear conditions in the atmospheric boundary layer.

To further characterize the inflow turbulence of the different cases, the integral length scale, the Kolmogorov length scale, and the Taylor-scale Reynolds number are shown in Table II. For the computation of the turbulence scales, Taylor’s frozen flow hypothesis is used to convert temporal scales into length scales. It should be noted that this hypothesis is only valid for small turbulence intensities and may introduce some error in the derived quantities for the highly turbulent flows investigated here. For all the following relations, see [39]. The integral length scale L_{11} is obtained by fitting an exponential to the autocorrelation function of the streamwise velocity component. The Kolmogorov length scale η is defined as $\eta = (\nu^3/\varepsilon)^{1/4}$. The dissipation rate ε is obtained via the streamwise velocity spectrum E_{11} . By compensating the spectrum with the Kolmogorov scaling $E_{11} \sim \varepsilon^{2/3} f^{-5/3} / \bar{u}$, where f is a frequency, the dissipation rate is computed as an average over the inertial subrange [40]:

$$\varepsilon = \left\langle \frac{2\pi}{\bar{u}} \left[\frac{f^{5/3} E_{11}}{18/55 C_K} \right]^{3/2} \right\rangle_{\text{inertial range}}. \quad (6)$$

Here, $C_K = 1.5$ is the Kolmogorov constant. However, this method is based on the assumption of homogeneous isotropic turbulence, which is likely not valid for the flow conditions involving mean velocity shear. The Taylor scale Reynolds number Re_λ is defined as $\text{Re}_\lambda = u'_{\text{rms}} \lambda / \nu$, where λ is the Taylor microscale. This Reynolds number is commonly used to characterize grid turbulence. The Taylor scale is obtained by

$$\lambda = \sqrt{\frac{15 \nu u'^2_{\text{rms}}}{\varepsilon}}. \quad (7)$$

The Reynolds number of grid turbulence is generally considered to be high if $\text{Re}_\lambda \sim 10^3$, which is achieved for all cases. It is somewhat surprising that the high-turbulence-intensity inflow had

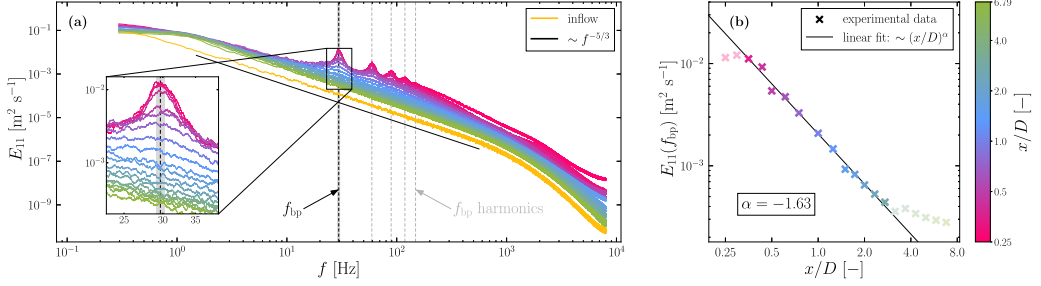


FIG. 6. (a) Inflow spectrum and wake spectra at the top of the rotor for the reference case at different downstream positions. f_{bp} is the blade pass frequency. The interval shown around f_{bp} corresponds to the region in which the average value is taken for the determination of the peaks. (b) Local maxima of the wake spectra around the blade pass frequency. Only the data points shown with solid markers are used for the linear fit.

approximately the same Re_λ as the reference case and that the high-shear inflow had a lower Re_λ than the reference case. In all cases, the integral scale is similar to or larger than the rotor diameter, which is generally also true for full-scale wind turbine flows. While a dependence of the integral scale on mean shear is not observed, it decreases with increasing turbulence intensity. Similarly, the Kolmogorov scale η decreases with turbulence intensity.

F. Quantification of tip vortex breakdown

In order to investigate the scaling of tip vortex breakdown, a quantitative measure of this breakdown is needed. Many studies use vorticity-based measures derived from flow visualization to quantify vortex strength [8,12]. However, such approaches are time consuming and computationally expensive, which makes large parameter scans challenging. Here, we are primarily interested in the rate of vortex breakdown, rather than absolute vortex strength. As such, the signature of the tip vortices in the streamwise velocity spectrum is used as a measure of vortex breakdown. By considering only the streamwise velocity component, this method neglects the three-dimensional structure of the tip vortices. However, for the purpose of deriving scaling laws, we consider this approach to be sufficient.

Figure 6(a) shows the velocity spectrum of the inflow at the rotor position as well as in the wake at different downstream positions for the reference case. In the wake, the $-5/3$ scaling in the inertial range is disrupted by the signature of the tip vortices. The highest deviation occurs close to the rotor, where the tip vortices cause the spectrum to exhibit a distinct peak at approximately the blade pass frequency $f_{bp} = 3f_{rot}$, where f_{rot} is the rotational frequency of the wind turbine. This is the frequency at which tip vortices are created at a specific azimuthal position along the rotor edge and thus the frequency at which they pass by a specific measurement location in the wake. Close to the rotor ($x/D \lesssim 0.5$), peaks also occur at frequencies equal to an integer multiple of the blade pass frequency. These peaks correspond to the harmonics of the first peak. The height of the first peak decreases with distance from the rotor. These signatures of the tip vortices in the wake velocity spectra have previously been observed in the literature [6,21,22,41,42].

We consider the height of the peak at f_{bp} to be related to the strength of the tip vortices (see Sec. III B). Thus, the average of the smoothed velocity spectrum within a 1 Hz interval around the blade pass frequency is taken as a measure of the strength of the vortices. The width of this interval is chosen such that the slope of the spectra does not significantly affect the determined peak height, even for small peaks. Details regarding the sensitivity of the peak height to the computation of the spectra are discussed in the Supplemental Material [32]. The resulting peak heights as a function of downstream position for the reference case are shown in Fig. 6(b) and further elaborated in Sec. III B.

III. RESULTS AND DISCUSSION

A. Evolution of the wake spectra

The streamwise velocity spectra for the reference case are shown in Fig. 6(a). They contain the distribution of turbulent kinetic energy in the streamwise velocity component E_{11} across the frequencies f that are present in the flow. The frequencies can be associated with the scales of the turbulence: low frequencies correspond to large scales, while high frequencies correspond to small scales. The inflow spectrum was obtained at the streamwise position of the rotor after removing the turbine, while the wake spectra were measured at $0.25 \leq x/D \leq 6.79$ downstream of the rotor. The inflow spectrum exhibits an inertial range of almost three decades, as shown by the $-5/3$ scaling, which is characteristic of high Reynolds number turbulence.

The downstream evolution of the wake spectra shows a complex scale-dependent behavior. Close to the rotor ($x/D \lesssim 1.5$), the wake spectra are dominated by the presence of the tip vortices, which appear to primarily affect the turbulence at scales equal to and smaller than the vortex spacing. As such, the spectral energy in the range $10^1 \text{ Hz} \lesssim f \lesssim 10^3 \text{ Hz}$ is higher than in the inflow, but decreases with downstream position. At frequencies lower than the blade pass frequency (larger scales), the spectral energy is also higher in the wake than in the inflow, which might be due to the generation of turbulent kinetic energy by the shear layer surrounding the wake. Interestingly, over $10^0 \text{ Hz} \lesssim f \lesssim 10^1 \text{ Hz}$, which is within the inertial range of the inflow spectrum but lower than the blade pass frequency, the spectral energy remains relatively constant with downstream position.

Farther downstream ($x/D \gtrsim 1.5$), the peak corresponding to the tip vortices is no longer visible in the spectra. However, the spectral energy in the inertial range does not follow the $-5/3$ scaling of the inflow spectrum. Only far from the rotor ($x/D \gtrsim 3$) are the wake spectra similar in shape to the inflow spectrum over the entire inertial and dissipation ranges. With increasing distance from the rotor, the spectra are shifted downward, indicating an overall decay of turbulent kinetic energy. Far from the rotor ($x/D = 6.79$), the spectrum is still shifted upward with respect to the inflow spectrum, indicating that the wake turbulence has not fully decayed. This is in agreement with previous studies of wake turbulence, e.g., [15].

At all downstream positions, the lowest frequencies ($f \lesssim 10^0 \text{ Hz}$) show a decrease of spectral energy, indicating a decay of these very large scales. This suggests that the turbulence at scales larger than the tip vortices is in equilibrium and slowly decaying, while the smaller scales are out of equilibrium due to the turbulence generated by the vortex breakdown. At the highest frequencies ($f \gtrsim 10^3 \text{ Hz}$), which extend into the dissipation range, the measurements closest to the rotor show the highest spectral energy. While the spectral energy at these frequencies generally decreases downstream, its functional form depends strongly on the exact frequency. However, due to the use of SF_6 to achieve Kolmogorov length scales $\eta \sim 10^{-5} \text{ m}$, the dissipation range was not fully resolved in these measurements.

B. Tip vortex breakdown

The inset in Fig. 6(a) shows a close-up of the peaks around the blade pass frequency in the streamwise velocity spectra. In the absence of flow visualization, it is not possible to directly relate these peaks to specific vortex behavior or breakdown mechanisms. Nevertheless, their gradual decay may serve as a relative measure of the rate of vortex breakdown in various flow conditions. The frequency at which these peaks are located in the spectrum is related to the rate at which the vortices appear at the measurement location, rather than their size. At $x/D = 0$, a tip vortex is generated every time a blade passes by the reference location, so that we expect the vortices to appear in the velocity signal as a periodic disturbance with a frequency of exactly f_{bp} . As they are convected downstream and interact with the surrounding flow, we expect them to wobble and gradually break up so that the rate at which they appear at a given measurement location begins to fluctuate [43]. This would cause the peaks to widen with increasing downstream position, which is what we observe in Fig. 6(a). As such, we interpret the magnitude of the peak to be a measure of the coherence of the

TABLE III. Parameters of the power law fit $E_{11}(f_{bp}, \xi) = c \xi^\alpha$ for the second regime of the downstream evolution of the peak heights in the wake spectra.

ID	α [–]	c [$10^{-3} \text{ m}^2 \text{ s}^{-1}$]	R^2 [–]
low shear	-1.54 ± 0.08	2.12 ± 0.07	0.992
low TI	-1.5 ± 0.2	2.7 ± 0.3	0.954
low TSR	-1.28 ± 0.04	4.1 ± 0.1	0.994
reference	-1.63 ± 0.04	2.05 ± 0.06	0.995
high TSR	-1.74 ± 0.04	0.96 ± 0.03	0.996
high TI	-1.46 ± 0.06	1.28 ± 0.06	0.992
high shear	-1.39 ± 0.09	1.47 ± 0.05	0.989

vortex and the regularity of its appearance at the measurement location: a flatter and wider peak implies a less coherent vortex or larger fluctuations in its location, both of which can be associated with vortex breakdown.

To investigate the rate of tip vortex breakdown, we quantify the height of the aforementioned peak in the spectrum at each downstream position as described in Sec. II F. Figure 6(b) shows the downstream evolution of the peak height for the reference case. In the logarithmic representation, three different regimes can be identified. In the first regime ($x/D \lesssim 0.3$), the peak height is relatively constant. This might indicate that in this regime, the interaction between tip vortices and the surrounding flow is only weak, and the vortices are mostly being advected. In the second regime ($0.3 \lesssim x/D \lesssim 2.4$), the peaks start to decrease rapidly, following a linear trend in the logarithmic representation. This implies a power law scaling of the form $E_{11}(f_{bp}, \xi) = c \xi^\alpha$ where $\xi = x/D$. The parameter c is the peak height at $\xi = 1$, and thus describes the vertical offset of the data. The parameter α is the slope of the linear fit and thus describes the rate of peak decrease. Since this scaling describes a decay process, α is negative. Comparing the extent of this regime with Fig. 6(a) shows that for these downstream positions the spectra transition from having a clear tip vortex signature to being similar in shape to the inflow spectrum. Therefore, this regime likely represents the breakdown of the tip vortices. In the third regime ($x/D \gtrsim 2.4$), the wake spectra are similar to the inflow spectrum. Here, the downstream evolution of the spectra at the blade pass frequency again seems to follow a power law, but at a much lower decay rate. As the spectra exhibit a clear inertial range in this regime, this decrease is presumably linked to decaying turbulence. In the following, we will investigate how variations in flow conditions affect the tip vortex breakdown. Therefore, we will focus on the second regime, for which the scaling parameters are shown in Table III.

C. Effects of shear and turbulence intensity

Variations in mean velocity shear [see Fig. 7(a)] and turbulence intensity [see Fig. 7(b)] do not lead to clear trends in the decay rate α in the second regime. However, the turbulence intensity affects the offset of the fitted curves such that high turbulence intensities lead to overall lower peak heights. This trend is already present at $x/D = 0.25$ downstream of the rotor, which may indicate that within the wake region studied here, the underlying process of the tip vortex breakdown is only weakly affected by the turbulence intensity. Instead, its impact on tip vortex breakdown might occur very close to the rotor, during or immediately after vortex formation, affecting the onset of vortex breakdown and thus the overall lifetime of the vortices. Interestingly, there is no notable difference in the breakdown process between the low and medium shear conditions, while the high shear condition seems to accelerate the breakdown process close to the rotor. Because mean velocity shear is a relatively large-scale flow feature compared to the scales of the tip vortices, they may only feel the shear at short time-scales if it is sufficiently strong locally. Due to the sparse sampling for the low and high shear cases, the existence of three regimes in these conditions cannot be confirmed with certainty. However, far from the rotor, the spectral energy at the blade pass frequency deviates

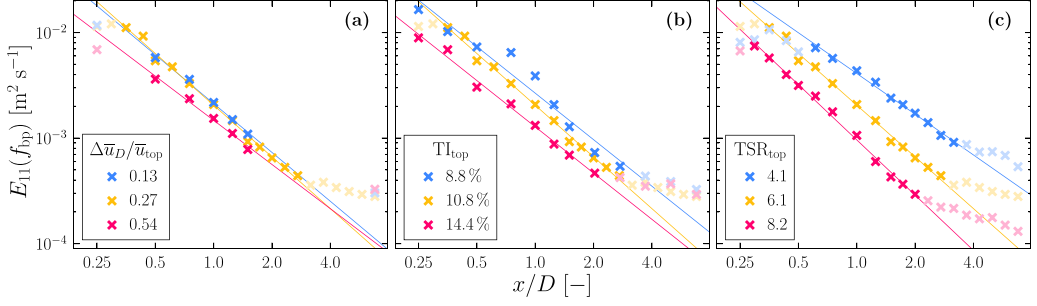


FIG. 7. Spectral peak heights corresponding to tip vortices at different downstream positions for varying (a) shear, (b) turbulence intensity, and (c) tip speed ratio. The lines correspond to power law fits. Only the data points shown with solid markers are used for the linear fit.

from the trend observed in the second regime, suggesting the presence of a third regime. In fact, the spectral energy in the third regime coincides for all shear and turbulence intensity conditions. This supports the idea that mean velocity shear and turbulence intensity mainly influence the tip vortex breakdown very close to the rotor without having a large impact on turbulence decay far from the rotor.

The scales at which the turbulence interacts with the tip vortices are best seen in the velocity spectra. Figure 8 shows inflow and wake spectra for the conditions with varying turbulence intensity. As expected, the inflow spectra are shifted vertically: higher turbulence intensity leads to more spectral energy at all scales, but interestingly, it also reduces the integral scale (see Table II). Nevertheless, the integral scale is always on the order of the rotor diameter.

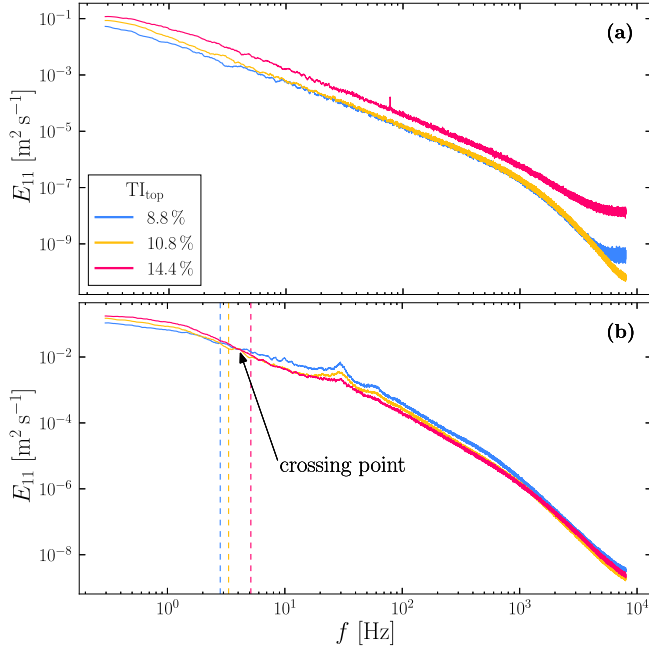


FIG. 8. (a) Inflow spectra and (b) wake spectra at $x/D = 0.75$ for different turbulence intensities in the inflow. The dashed lines correspond to the integral scales.

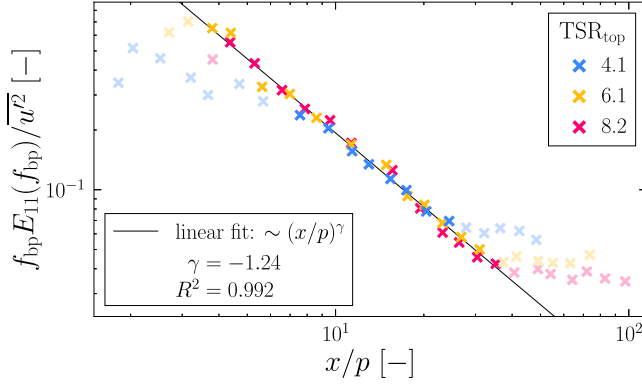


FIG. 9. Spectral peak heights for all tip speed ratio cases normalized by the local streamwise variance $\overline{u^2}$ and the pitch p .

At the low frequencies (large scales), the wake spectra follow the same trend as the inflow spectra, though the spectral energy is higher for all cases, presumably due to turbulence generated by the shear layer. However, at scales close to the integral scales, a crossing point occurs after which the trend is reversed, so that at the scales of the tip vortices, higher turbulence intensity leads to less spectral energy. In the dissipation range, the spectra collapse. This may indicate that it is primarily the large scales of the turbulence that interact with the vortices to facilitate their breakdown and the decay of the turbulence generated by this breakdown. The observed crossing point and the spectral energy at the large scales remain relatively constant throughout the range observed here (up to $x/D = 1.50$), which raises the question whether the turbulence generated by the vortex breakdown inhibits the decay of the large-scale turbulence generated by the shear layer. This shows the importance of considering which scales are present in the turbulence and how they interact with the tip vortices, rather than using only the turbulence intensity to characterize the flow.

D. Effects of tip speed ratio

The tip speed ratio appears to have the strongest effect on tip vortex breakdown. It affects both the onset of the second regime (reflected in a higher offset parameter c) and the breakdown rate α within this regime: higher tip speed ratios lead to earlier onset and faster breakdown, as shown in Fig. 7(c). This could be connected to two effects: first, an increase in tip speed ratio results in slightly weaker tip vortices [12]. Second, it reduces the spacing between subsequent tip vortices, which enables earlier and stronger interactions between them. At lower tip speed ratios, the larger spacing delays the vortex breakdown mechanisms associated with vortex-vortex interactions. In addition, the increased strength of the tip vortices at low tip speed ratios may lead to longer advection before strong interactions with the surrounding turbulence occur.

To investigate the influence of the spacing on the tip vortex breakdown, Fig. 9 shows the peak heights normalized by the streamwise contribution to the local turbulence kinetic energy and the pitch $p = \bar{u}_{\text{top}}/f_{\text{bp}}$, which is a measure of the distance between subsequent vortices. In this representation, we observe a single power law for all tip speed ratio cases, which indicates that the turbulence kinetic energy and the vortex spacing might be the dominant parameters in the second regime.

IV. CONCLUSION

We conducted a laboratory study of a wind turbine wake in a high Reynolds number ($\text{Re}_D \sim 10^6$) turbulent flow. We demonstrate that the combination of a pressurized wind tunnel and an active turbulence grid allows for the recreation of realistic atmospheric boundary layer flow characteristics

in a controllable and repeatable way. This enables us to investigate specific flow parameters like mean shear and turbulence intensity in isolation, while maintaining dynamic similarity with full-scale wind turbine flows.

We investigated the effect of various flow conditions on the scaling of the tip vortex breakdown process. The inflow conditions considered here were significantly more turbulent than those of most previous investigations of this phenomenon, so that interactions of the turbulence with the tip vortices were expected to be important for the breakdown process. We show that within the wake region investigated here, three distinct regimes can be identified, which we attribute to vortex advection, vortex breakdown, and turbulence decay. Within the vortex breakdown regime, the breakdown process is described reasonably well by a power law scaling. The tip speed ratio has a significant effect on the breakdown rate within this regime, while turbulence intensity appears to primarily affect the breakdown process farther upstream without affecting the breakdown rate in the observed region. The impact of mean velocity shear was overall less pronounced and did not notably affect the breakdown rate in the observed region. This points to the importance of the tip speed ratio for the tip vortex breakdown process even in a highly turbulent environment. We show that the relevant length scale here is the distance between subsequent vortices. This underlines that the interaction between tip vortices is an important breakdown mechanism even in highly turbulent conditions. The chosen tip speed ratio for wind turbines is commonly based solely on considerations regarding the power output of the singular turbine. For wind farms, in which wake recovery is crucial, the aggregated power output might benefit from slightly higher tip speed ratios, as these may lead to faster tip vortex breakdown.

We further show that the different length scales in the turbulence interact differently with the tip vortices, and the largest scales are possibly most important for tip vortex breakdown. The turbulence intensity as a single parameter is unlikely to accurately capture this complexity. Rather, the relationship between integral scales and vortex scales should be investigated further.

Our results underline the importance of the inflow conditions for the tip vortex breakdown process. Even small changes in turbulence intensity impact how far downstream the signature of the tip vortices persists in the wake, so that scalings observed under laminar inflow conditions are unlikely to accurately describe the vortex breakdown process in highly turbulent atmospheric conditions. Under highly turbulent conditions, tip vortex breakdown appears to be initiated very close to the rotor. Further study is necessary to investigate the effect of the inflow on the initiation of the breakdown close to the rotor.

ACKNOWLEDGMENTS

The authors would like to thank Julian Jüchter at the Carl von Ossietzky University of Oldenburg for adapting the model wind turbine to the experimental conditions of this study and for providing technical support throughout the experiments. We thank Michael Hölling and ForWind for providing us with the model wind turbine for this study. We thank Constantin Schettler for his assistance in designing the experimental setup and Andreas Renner, Andreas Kopp, Marcel Meyer, and Artur Kubitzek for their support in setting up the experiment. We also thank Eberhard Bodenschatz for helpful discussions.

DATA AVAILABILITY

The data that support the findings of this article are openly available [44].

-
- [1] R. J. Barthelmie, S. C. Pryor, S. T. Frandsen, K. S. Hansen, J. G. Schepers, K. Rados, W. Schlez, A. Neubert, L. E. Jensen, and S. Neckelmann, Quantifying the impact of wind turbine wakes on power output at offshore wind farms, *J. Atmos. Ocean. Technol.* **27**, 1302 (2010).

- [2] K. S. Hansen, R. J. Barthelmie, L. E. Jensen, and A. Sommer, The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm, *Wind Energy* **15**, 183 (2012).
- [3] K. Thomsen and P. Sørensen, Fatigue loads for wind turbines operating in wakes, *J. Wind Eng. Ind. Aerodyn.* **80**, 121 (1999).
- [4] L. Vermeer, J. Sørensen, and A. Crespo, Wind turbine wake aerodynamics, *Prog. Aerosp. Sci.* **39**, 467 (2003).
- [5] F. Porté-Agel, M. Bastankhah, and S. Shamsoddin, Wind-turbine and wind-farm flows: A review, *Bound.-Layer Meteorol.* **174**, 1 (2020).
- [6] I. Neunaber, M. Hölling, R. J. A. M. Stevens, G. Schepers, and J. Peinke, Distinct turbulent regions in the wake of a wind turbine and their inflow-dependent locations: The creation of a wake map, *Energies* **13**, 5392 (2020).
- [7] L. E. Lignarolo, D. Ragni, C. Simao Ferreira, and G. G. Van Bussel, Experimental quantification of the entrainment of kinetic energy and production of turbulence in the wake of a wind turbine with particle image velocimetry, in *32nd ASME Wind Energy Symposium* (American Institute of Aeronautics and Astronautics, National Harbor, Maryland, 2014).
- [8] L. Lignarolo, D. Ragni, C. Krishnaswami, Q. Chen, C. Simão Ferreira, and G. Van Bussel, Experimental analysis of the wake of a horizontal-axis wind-turbine model, *Renew. Energy* **70**, 31 (2014).
- [9] S. Ivanell, R. Mikkelsen, J. N. Sørensen, and D. Henningson, Stability analysis of the tip vortices of a wind turbine, *Wind Energy* **13**, 705 (2010).
- [10] T. Leweke, S. Le Dizès, and C. H. Williamson, Dynamics and instabilities of vortex pairs, *Annu. Rev. Fluid Mech.* **48**, 507 (2016).
- [11] A. Posa, R. Broglia, and E. Balaras, Instability of the tip vortices shed by an axial-flow turbine in uniform flow, *J. Fluid Mech.* **920**, A19 (2021).
- [12] H. Hu, Z. Yang, and P. Sarkar, Dynamic wind loads and wake characteristics of a wind turbine model in an atmospheric boundary layer wind, *Exp. Fluids* **52**, 1277 (2012).
- [13] H. C. Ghimire and S. C. C. Bailey, An experimental investigation of wing-tip vortex decay in turbulence, *Phys. Fluids* **29**, 037108 (2017).
- [14] H. C. Ghimire and S. C. C. Bailey, Experimental examination of vorticity stripping from a wing-tip vortex in free-stream turbulence, *Phys. Rev. Fluids* **3**, 034702 (2018).
- [15] S. Gambuzza and B. Ganapathisubramani, The influence of free stream turbulence on the development of a wind turbine wake, *J. Fluid Mech.* **963**, A19 (2023).
- [16] W. van der Deijl, F. Schmitt, C. Sicot, S. Barre, M. Hölling, and M. Obligado, Effect of background turbulence on the wakes of horizontal-axis and vertical-axis wind turbines, *J. Wind Eng. Ind. Aerodyn.* **253**, 105877 (2024).
- [17] P. C. Yen, Y. Li, F. Scarano, and W. Yu, Near-wake behavior of an asymmetric wind turbine rotor, *Wind Energ. Sci.* **10**, 1775 (2025).
- [18] L. P. Chamorro and F. Porté-Agel, A wind-tunnel investigation of wind-turbine wakes: Boundary-layer turbulence effects, *Bound.-Layer Meteorol.* **132**, 129 (2009).
- [19] L. Li, R. J. Hearst, M. A. Ferreira, and B. Ganapathisubramani, The near-field of a laboratory-scale wind turbine in tailored turbulent shear flows, *Renew. Energy* **149**, 735 (2020).
- [20] A. Parinam, P. Benard, D. V. Terzi, and A. Viré, Large-Eddy simulations of wind turbine wakes in sheared inflows, *J. Phys.: Conf. Ser.* **2505**, 012039 (2023).
- [21] A. Piqué, M. A. Miller, and M. Hultmark, Laboratory investigation of the near and intermediate wake of a wind turbine at very high Reynolds numbers, *Exp. Fluids* **63**, 106 (2022).
- [22] A. Piqué, M. A. Miller, and M. Hultmark, Dominant flow features in the wake of a wind turbine at high Reynolds numbers, *J. Renew. Sustain. Energy* **14**, 033304 (2022).
- [23] E. Bodenschatz, G. P. Bewley, H. Nobach, M. Sinhuber, and H. Xu, Variable density turbulence tunnel facility, *Rev. Sci. Instrum.* **85**, 093908 (2014).
- [24] H. E. Cekli and W. van de Water, Tailoring turbulence with an active grid, *Exp. Fluids* **49**, 409 (2010).
- [25] R. J. Hearst and B. Ganapathisubramani, Tailoring incoming shear and turbulence profiles for laboratory-scale wind turbines, *Wind Energy* **20**, 2021 (2017).

- [26] Y. Jooss, R. J. Hearst, and T. Bracchi, Influence of incoming turbulence and shear on the flow field and performance of a laboratory-scale roof-mounted vertical axis wind turbine, *J. Renew. Sustain. Energy* **15**, 063302 (2023).
- [27] M. Hideharu, Realization of a large-scale turbulence field in a small wind tunnel, *Fluid Dyn. Res.* **8**, 53 (1991).
- [28] P. Knebel, A. Kittel, and J. Peinke, Atmospheric wind field conditions generated by active grids, *Exp. Fluids* **51**, 471 (2011).
- [29] L. Neuhaus, M. Hölling, W. J. T. Bos, and J. Peinke, Generation of atmospheric turbulence with unprecedentedly large Reynolds number in a wind tunnel, *Phys. Rev. Lett.* **125**, 154503 (2020).
- [30] K. P. Griffin, N. J. Wei, E. Bodenschatz, and G. P. Bewley, Control of long-range correlations in turbulence, *Exp. Fluids* **60**, 55 (2019).
- [31] L. Kröger, J. Frederik, J.-W. van Wingerden, J. Peinke, and M. Hölling, Generation of user defined turbulent inflow conditions by an active grid for validation experiments, *J. Phys.: Conf. Ser.* **1037**, 052002 (2018).
- [32] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/5phx-7dhk> for more details on the active grid protocols used in this study as well as a description of the averaging used for the velocity spectra.
- [33] J. Schottler, A. Hölling, J. Peinke, and M. Hölling, Design and implementation of a controllable model wind turbine for experimental studies, *J. Phys.: Conf. Ser.* **753**, 072030 (2016).
- [34] J Jüchter, J. Peinke, L. J. Lukassen, and M. Hölling, Reduction and analysis of rotor blade misalignments on a model wind turbine, *J. Phys.: Conf. Ser.* **2265**, 022071 (2022).
- [35] N. O. Jensen, A note on wind generator interaction, Technical report Ris-M-2411 (Risø National Laboratory, 1983).
- [36] M. Bastankhah and F. Porté-Agel, A new analytical model for wind-turbine wakes, *Renew. Energy* **70**, 116 (2014).
- [37] P. Welch, The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms, *IEEE Transactions on Audio and Electroacoustics* **15**, 70 (1967).
- [38] Bundesamt für Seeschifffahrt und Hydrographie (BSH), Fino3 measurement data, Offshore measurement platform FINO3, available at <https://www.fino3.de/en/news-data/live-data.html> (2025), accessed May 15, 2025.
- [39] S. B. Pope, *Turbulent Flows*, 1st ed. (Cambridge University Press, New York, 2000).
- [40] M. Schröder, T. Bätge, E. Bodenschatz, M. Wilczek, and G. Bagheri, Estimating the turbulent kinetic energy dissipation rate from one-dimensional velocity measurements in time, *Atmos. Meas. Tech.* **17**, 627 (2024).
- [41] N. Biswas and O. R. Buxton, Effect of tip speed ratio on coherent dynamics in the near wake of a model wind turbine, *J. Fluid Mech.* **979**, A34 (2024).
- [42] W. Zhang, C. D. Markfort, and F. Porté-Agel, Near-wake flow structure downwind of a wind turbine in a turbulent boundary layer, *Exp. Fluids* **52**, 1219 (2012).
- [43] M. Couliou, S. Yadala, G. K. Jankee, I. Neunaber, and R. J. Hearst, The effect of freestream turbulence on wing-tip vortex meandering and deformation, *Int. J. Heat Fluid Flow* **117**, 110013 (2026).
- [44] M. Grunwald and C. E. Brunner, Effect of inflow conditions on tip vortex breakdown in a high Reynolds number wind turbine wake, *Edmond* (2025).