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# Roughness Effects on Wind-Turbine Wake Dynamics in a Boundary-Layer Wind Tunnel

E. Barlas  $\cdot$  S. Buckingham  $\cdot$  J. van Beeck

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Abstract Increasing demand in wind energy has resulted in increasingly clustered wind farms, 1 2 and raised the interest in wake research dramatically in the last couple of years. To this end, the present work employs an experimental approach with scaled three-bladed wind-turbine models 3 in a large boundary-layer wind-tunnel. Time-resolved measurements are carried out with three-4 component hot-wire anemometer in the mid-vertical plane of the wake up to a downstream distance 5 of eleven turbine diameters. The major issue addressed is the wake dynamics i.e. the flow and 6 turbulence characteristics as well as spectral content under two different neutral boundary-layer 7 inflow conditions. The wind tunnel is arranged with and without roughened surfaces in order to 8 mimic moderately rough and smooth conditions. The inflow characterization is carried out by using 9 all three velocity components, while the rest of the study is focused on the streamwise component's 10 evolution. The results show an earlier wake recovery, i.e. the velocity deficit due to the turbine 11 is less persistent for the rough case due to higher incoming turbulence levels. This paves the way 12 for enhanced mixing from higher momentum regions of the boundary layer towards the centre of 13 the wake. The investigation on the turbulent shear stresses is in line with this observation as well. 14 Moreover, common as well as distinguishing features of the turbulent-scales evolution are detected 15 for rough and smooth inflow boundary-layer conditions. Wake meandering disappears for rough 16 inflow conditions but persists for smooth case with a Strouhal number similar to that of a solid 17 disk wake. 18

<sup>19</sup> Keywords Roughness effects · Three-component hot-wire anemometer · Wind-tunnel experiment · Wind-tunnel experiment ·

20 Wind-turbine wakes

## 1 Introduction

The number of wind farms worldwide is increasing resulting in turbines that are situated in an increasingly clustered manner. This grouping gives rise to two main disadvantages in terms of

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cost of energy. First, a wind turbine operating in the wake has a reduced power production due to lower incident wind speed. Secondly, the large-scale and small-scale structures in the wake results in added turbulence that decreases the lifetime of downstream turbines due to increased fatigue. These are two well-known issues for wind-farm wake aerodynamics. Nevertheless a deep enough understanding has not been fully reached, as illustrated by relatively poorly performing computational or analytical models (Crespo et al. 1999; Sanderse et al. 2011; Gaumond et al. 2012).

The shortcomings of the models are mostly due to lack of understanding of the complex in-30 teraction between the atmospheric boundary layer and wind turbine, as pointed out by Rados et 31 al. (2009). Additionally, the unsteady nature of the wake gives rise to other problems such as the 32 meandering phenomenon (Bingol et al., 2010). In simplest terms, it is the movement of the wake 33 as a whole in both the horizontal and vertical directions as the wake is convected downstream. 34 This transport process is modelled by Larsen et al. (2008) assuming the wakes to act as passive 35 tracers driven by the large-scale turbulence structures. This does not necessarily yield a periodic 36 37 behaviour. However, there are studies in the literature that relate the meandering behaviour to the intrinsic instabilities as in bluff-body vortex shedding (Medici and Alfredsson, 2006), even though 38 this relation has been contradicted by Devinant et al. (2011) and Larsen et al. (2008). 39

The aim of this work is to provide additional data to the existing experimental wake database with tailored-designed rotating turbine models and state-of-the-art experimental techniques in order to extract a physical understanding of how boundary-layer turbulence affects the spatial wake development. In addition to this, the meandering phenomenon is investigated with respect to the evolution of turbulent length scales through spectral analysis.

#### 45 2 Experimental Set-up

#### <sup>46</sup> 2.1 Wind-Turbine Model

<sup>47</sup> The three-bladed wind-turbine model has a 150-mm diameter and a 130-mm hub height and is <sup>48</sup> representative of a scaled 2 MW offshore wind turbine (see Fig. 1).



Fig. 1 Wind-turbine model dimensions and front view.

The working principle of the model is the following: a small direct current (DC) motor inside the motor housing (nacelle) is used as a generator. It is connected to an electrical circuit with which it can be counter-loaded in order to extract power from the airflow. This process does not only extract power, but also decreases the turbine rotational speed, which is tracked via the encoder

 $\mathbf{2}$ 

<sup>53</sup> mounted to the motor. Thereby the tip-speed ratio,  $\lambda$ , ( $\lambda = \omega \cdot r / U_h$  where  $\omega$  is the angular <sup>54</sup> velocity, r is the rotor radius and  $U_h$  is the hub-height speed) can be observed and controlled with <sup>55</sup> the variable resistance in the circuit.

The tip-speed ratio is an important parameter, since the thrust of the turbine is directly related to it. The characterization of the model, namely the relationship of the electrical resistance versus tip-speed ratio, was carried out before the experiments. Since there were no force measurements, comparative studies with two different boundary-layer conditions were carried out under same tipspeed ratio ( $\lambda = 5$ ). Thereby, the aim has been to concentrate solely on the boundary-layer effects on the wind-turbine wake, while the thrust remained constant.

Moreover, the blades were designed based on blade element momentum theory considering the 62 low Reynolds numbers ( $\approx 10^5$ ) that is reached and for a design tip-speed ratio of 5. During the de-63 sign process a thin airfoil section GM15 was used and manufactured via three-dimensional printing. 64 A detailed analysis of the blade design can be found in Bossuyt (2013). It is worthwhile mention-65 ing that the wind-turbine wake studies that are carried out in wind tunnels with miniature wind 66 turbines can result in misleading conclusions because of the large scaling ratios ( $\approx 1.500$ ). In other 67 words, the experiments that are conducted at lower Reynolds numbers, to full scale conditions 68 may affect the flow statistics. However, according to Chamorro et al. (2012) the Reynolds num-69 ber independence (on the basis of the rotor diameter and hub-height speed) for the higher order 70 statistics (i.e. turbulence intensity and kinematic shear stress) was reached for values over 9.3  $\times$ 71  $10^4$ , while this value was even lower for the mean speed statistics ( $\approx 4.8 \times 10^4$ ). The present set 72 of experiments were carried out at a hub-height speed of 8 m s<sup>-1</sup>. Based on the turbine diameter 73 of 0.15 m, the reached Reynolds number was  $8.5 \times 10^4$ . 74

## <sup>75</sup> 2.2 Experimental Facility and Measurement Technique

The experiments were carried out at the VKI-L1B wind tunnel. The closed return circuit tunnel 76 has a contraction ratio of 4.7 and is powered by a variable-speed DC motor of 580 kW driving two 77 contra rotation fans of 4.2 m diameter. The L1B configuration is of interest for wind-engineering 78 applications among other tunnel settings. In this configuration the rectangular test section is 2 m 79 high, 3 m wide and 20 m long with the possibility of a roughened floor to allow for the growth of a 80 scaled down turbulent boundary layer similar in nature to the lower part of the neutral atmospheric 81 boundary layer. The end of the test section is equipped with a 2.6 m diameter turn table on which 82 the model to be tested is placed. 83

The measurement probe used during the campaigns was a three-component Dantec 55P91 hot-84 wire anemometer (3C-HWA). In addition to the standard velocity calibration the 3C-HWA requires 85 also a one-time directional calibration. This is important in order to decompose the velocity into 86 87 its components correctly. The directional sensitivity of tri-axial probes is characterized by both a 88 yaw and a pitch coefficient. In this study, the coefficients that were calculated via the calibration 89 performed by Fruytier (1993) were used. For a more detailed description of the calibration and decomposition of the velocity components procedure, refer to Annex A of Conan (2012). The 3C-90 HWA is indeed an important tool to acquire all three components in a time-resolved manner. On 91 the other hand, it might be disadvantageous, since the spatial resolution is lower in comparison to a 92 single component anemometer and the measurements are only reliable for flow within  $\pm$  35 degree 93 of the cone. This is an important factor that one should keep in mind during the data acquisition 94 and post processing periods. 95

The measurements were taken at the mid vertical plane of the wake (x/D = -1, 1, 2, 3, 4, 5, 7, 7)

97 9, 11; where x and D is the streamwise coordinate and the turbine diameter, respectively). At each 98 downstream location 28 measurement points were covered vertically. Starting from 30-mm above

ground  $(z/z_{tip} \approx 0.15$  where z, the vertical coordinate is normalized with  $z_{tip}$ , the height at the

top tip of the turbine model) to 260-mm  $(z/z_{tip} \approx 1.3)$  the points are separated with increments



Fig. 2 a) Three-component HWA set-up installed in VKI L1-B wind tunnel test section. b) Dots representing measurement points at various downstream locations expressed in turbine diameter (D).

<sup>101</sup> of 10-mm and above that until 340-mm  $(z/z_{tip} \approx 1.7)$  the distances were 20-mm. At each point <sup>102</sup> the measurements were made at 3 kHz, for at least 120 seconds and filtered at 1 kHz. In Fig. 2b, <sup>103</sup> each point represents the measurement positions for the 3C-HWA instrument.

During the uncertainty analysis, bias and random errors were taken into account. However, considering the long enough observation time the random error is expected to be low. The bias error was calculated first considering a single component hot wire and then this was assumed to be valid for all three components. Subsequently, the errors that are caused by the rotation and Jørgensen matrices, are added together (see Fig. 3). The propagation was done by estimating a  $2^{\circ}$ variation on the angles used in the rotational matrix and 5% error on pitch and yaw coefficients. Overall, this leads to an error of 7% for the velocity range of interest; 7 to 9 m s<sup>-1</sup>.



Fig. 3 Bias error calculated as function of the reference flow velocity.

## 111 2.3 Inflow Characterization

As aforementioned, two different boundary layers were simulated in the wind tunnel. For the smooth-wall boundary layer (see Fig. 4b) no roughness elements were added to the test section so that the free surface provides a moderate boundary-layer growth. On the other hand, for the rough-wall boundary layer the test section (12 m) was equipped with 95-mm high cups until 3 m upstream of the model after which the transition blocks are used in order to ensure flow stability (see <sup>117</sup> Fig. 4a). Here, a brief characterization of the two different inflow conditions is carried out, namely <sup>118</sup> the aerodynamic roughness, the turbulence intensities and the length scales are investigated.



Fig. 4 Photos from two set-ups of the wind tunnel; a) Rough-wall boundary layer, b) Smooth-wall boundary layer

The friction velocity  $(u_*)$  was calculated via skin friction coefficient  $(C_f)$ . By plotting the mean wind speed versus height in logarithmic scale, one can use the slope of the linear curve in the logarithmic layer  $(\gamma)$  in order to calculate skin friction coefficient using the expression  $C_f = 2 \cdot (\gamma/2.5 \cdot U_\infty)^2$ . The aerodynamic roughness length  $(z_0)$  was then calculated using

$$\frac{U_{ref}}{u_*} = \frac{1}{\kappa} \cdot \ln(\frac{z}{z_0}),\tag{1}$$

where  $U_{ref}$  is the reference velocity,  $u_*$  is the friction velocity,  $\kappa$  is the von Karman constant equal to 0.41, z is the reference height. In addition, the power-law relationship was calculated from

$$\frac{U}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha},\tag{2}$$

where  $\alpha$  is the power-law exponent, known as the Hellmann coefficient,  $z_{ref}$  and  $U_{ref}$  are the 125 reference height and velocity, respectively. The exponent was calculated with the values that were 126 measured at the lowest and the highest locations where the blade tip passes. The results yield 127 friction velocities  $(u_*)$  of 0.56 m s<sup>-1</sup>, 0.30 m s<sup>-1</sup>; values of aerodynamic roughness length  $(z_0)$ 128 0.4-mm, 0.018-mm and the power-law exponents ( $\alpha$ ) of 0.3 and 0.16 for the two cases which are 129 referred as the rough case and smooth case, respectively. Figures 5-7 show the mean velocities ( $\overline{U}$ , 130  $\overline{V}, \overline{W}$ ) and standard deviation profiles  $(\sigma_U, \sigma_V, \sigma_W)$  normalized with the hub-height speed  $(U_h)$ 131 for all three velocity components; in the streamwise (x), spanwise (y) and vertical (z) directions, 132 respectively. In addition, the length scale distributions  $(L_u, L_v, L_w)$  were depicted with the same 133 coordinate system. They were calculated via autocorrelation in time and the temporal information 134 was transformed into spatial by Taylor's hypothesis which postulates that the mean velocity is the 135 convection velocity of the turbulence. They are non-dimensionalized with respect to the turbine 136 diameter (0.15 m), since this will be relevant for the following sections. 137



Fig. 5 a) Streamwise velocity component normalized with the hub-height wind speed. b) Streamwise turbulence intensity c) Streamwise turbulent length scales normalized with the turbine diameter. For all plots, squares represent rough case inflow conditions and stars represent smooth case inflow conditions



Fig. 6 a) Spanwise velocity component normalized with the hub-height wind speed. b) Spanwise turbulence intensity c) Spanwise turbulent length scales normalized with the turbine diameter. For all plots, squares represent rough case inflow conditions and stars represent smooth case inflow conditions

The streamwise velocity component for the smooth case has higher gradients but lower turbulence levels, while this is the opposite for the rough case. Additionally, it is observed that neither of the streamwise velocity component profiles reach the free stream. This ensures that the turbine models will be fully immersed in the boundary-layer flow. The earlier work on boundary-layer modelling at the L1-B wind tunnel by Conan (2012) shows that the boundary-layer depths for both cases are higher than 0.5 m. With these two configurations the turbine model will be exposed to different shear-flow conditions. Similar comparative studies are found in the literature, in which the



Fig. 7 a) Vertical velocity component normalized with the hub-height wind speed. b) Vertical turbulence intensity c) Vertical turbulent length scales normalized with the turbine diameter. For all plots, squares represent rough case inflow conditions and stars represent smooth case inflow conditions

experiments were conducted by keeping the hub-height speed same. This was indeed the case for this present experimental campaign. Regarding the turbulent length scales distribution, it is seen that both cases contain large scales in comparison to the turbine diameter. However, structures of the rough case are much smaller, as they are 'destroyed' by the cups located in the upstream part of the test section.

Additionally, the longitudinal length scales were compared to Counihan's empirical expression;  $L_U x = B * z^m$  where B and m are roughness dependent parameters (Counihan, 1975). The results (see Fig. 8) show that the scales in the wind tunnel follow the correct trend for two different scaling factors.



Fig. 8 Comparison of longitudinal length scales for the two different wind tunnel configurations and the corresponding empirical expression in Counihan (1975)

Furthermore, the development of the flow within the test section was investigated. Particularly 154 for the rough case it is important that the flow without the model does not go through a significant 155 change along the test section. In order to illustrate this streamwise velocity component and turbu-156 lence intensity profiles at the beginning (x = 0) and the middle of the test section (x = 1.4 m) is 157 shown in Fig. 9. The measurements were carried out in earlier work (Conan, 2012) and normaliza-158 tion was done with the wind speed at 90-cm, represented as  $U_{90}$ . The results show a reasonable fit to 159 each other. The maximum variation of turbulence intensity was calculated as 7.5 % and this value 160 was even lower for the streamwise velocity component. Considering that the furthest measurement 161 point corresponds to 1.8 m far from the beginning of the test section, it was concluded that this 162 study is a correct representation of the boundary layer effects. 163



Fig. 9 a) Streamwise velocity component and b) Streamwise turbulence intensity at the beginning (x = 0) and the middle (x = 1.4 m) of the centerline of the wind tunnel turntable normalized at z = 0.9 m.

#### <sup>164</sup> 3 Results and Discussion

<sup>165</sup> 3.1 Wake Dynamics: Velocity and Turbulence Evolution

The spatial distribution of the streamwise velocity component at the mid-vertical plane of the wake 166 is shown in Fig. 10. The profiles at the upstream of the turbine was obtained during the inflow 167 characterization without the turbine. The results clearly indicate an earlier wake recovery for the 168 rough case, where the incoming turbulence levels are higher. However, the wake deficit does not lose 169 its effect entirely as far as 11D for neither of the cases (see Fig. 11). It is clear that the streamwise 170 velocity component distribution at the wake is not axisymmetric. This is expected as the incoming 171 flow is not axisymmetric either. On the other hand, it is interesting to notice that for the rough 172 case, the wake deficit at the region lower than the hub height recovers earlier in comparison to 173 the region higher than the hub height. This is contradictory with the recently published work on 174 analytical wake modelling with Gaussian approach by Bastankhah and Porte-Agel (2014) in which 175 an axisymmetric wake deficit profile is assumed. Nevertheless, axisymmetry is indeed present for 176 the smooth case. 177



Fig. 10 Averaged streamwise velocity component at the mid-vertical plane of the wake normalized with the hub-height speed. Black dots represent the measurement points. Top: Smooth Wall Case. Bottom: Rough Wall Case.



Fig. 11 Averaged streamwise velocity component profiles normalized with the hub-height speed. Continuous starred line: Smooth case wake. Stars: Smooth case inflow. Continuous circled line: Rough case wake. Circles: Rough case inflow.

As aforementioned, the mean speed is not the only parameter of interest. The increased turbulence levels may result in increased fatigue due to the loading variations along the blade span or early failure of pitch and yaw mechanisms. The turbulence intensity levels of both cases are shown <sup>181</sup> in Fig. 12. Common point for both cases is that the highest values are reached around the tip region <sup>182</sup> where the strong shear contribution to the turbulence production is significant. On the other hand, <sup>183</sup> the high level of turbulence is spread to a larger region for the rough case and the peak values are <sup>184</sup> reached at around 1-2D downwind distance, while this is further downstream for the smooth case <sup>185</sup> (3-4D). This issue is elaborated via the shear stress distribution later on (see Fig. 13).



Fig. 12 Stream-wise Turbulence Intensity  $(\sigma_u/\overline{U_h})$ . Top: Smooth wall case. Bottom: Rough wall case.

Additionally the evolution of the maximum added turbulence was investigated. The added 186 turbulence is defined as  $I^+ = \sqrt{I_{wake}^2 - I_{inflow}^2}$  where  $I_{wake}$  and  $I_{inflow}$  are the turbulence levels 187 at the wake and at the incoming flow, respectively. It is a common procedure to seek a relationship 188 between the decay of the maximum  $I^+$  values and the downwind distance from the turbine in 189 meters. This study yielded with the order of  $x^{-0.5}$  and  $x^{-0.6}$  for the smooth case and rough case 190 respectively. Since the added turbulence decay will be quicker with a faster wake recovery, the 191 results are in agreement with the flow physics. Moreover, these values were in the range of the 192 similar studies by Ainslie (1988) and Chamorro et al. (2009) in which the power coefficients were 193 -2/3 and from -0.3 to -0.5, respectively 194

Another important concept for wake dynamics is the kinematic shear stresses (-u'w') that give 195 196 insight to the momentum transfer in the flow. The results (see Fig. 13) show that these stresses have positive values above the tip region where the transfer takes place from the higher momentum 197 regions of the boundary layer (above wake) towards the wake centre. Similarly, in the bottom 198 region these stresses are negative which stands for the upwards momentum transfer from the lower 199 region of the boundary layer again to the core of the wake. There is ongoing work to relate this 200 energy transfer to the power produced by turbines for a fully developed wind turbine boundary 201 layer which occurs after a sufficient number of turbines (Newman et al. 2013). Even though the 202 trend is the same for both of the boundary-layer cases, the magnitude is higher for the rough 203 case, which is associated with higher turbulent fluxes. Another distinguishing feature is that the 204 highest values of the stresses are reached at 2-3D for the rough case and 4-5D for the smooth 205 case. These two statements are in agreement with the wake recovery and its dynamics for various 206 atmospheric conditions. It is observed that as the wake develops downstream, the stress levels 207 become lower however, their effect is visible in a wider region which is also expected, considering 208 the wake expansion and the wake deficit. 209



Fig. 13 Kinematic shear stresses  $(-u'w'/U_h^2)$  for two different boundary layer configurations. Top: Smooth wall case. Bottom: Rough wall case.

210 3.2 Near Wake Spectral Content

An interesting study on the spectral analysis with a similar set-up to the present work was carried out by Chamorro et al. (2012). It was suggested to use the evolution of the turbulent length scales in order to conceptualize and model the turbine as an active filter. This means that in certain regions the turbine is able to generate or amplify some frequencies, while damping some others. The results of the present study are in line with this concept. To illustrate this, spectra at three measurement points, namely: *below the hub, at the tip* and *above 1.5 times the tip height*, are shown in Fig. 14 where the rough case and the smooth case spectra are also compared.

It is observed that for both cases, the very-large scale structures at the incoming flow that 218 characterize the turbulent boundary layer are indeed destroyed in the area below the nacelle, with 219 a cut-off frequency of  $f/f_t \approx 0.09$  where  $f_t$  is the turbine rotational frequency. Therefore, the 220 analogy of the turbine being a high pass filter in this region can still be valid with a minor change 221 of the cut-off frequency since this value is around 0.1 in Chamorro et al. (2012). On the other 222 hand, not all of the large scales are fully broken down for the smooth case. The turbine distinctly 223 excites a specific low frequency at the regions below hub and around tip. This low frequency, which 224 is believed to be caused by the wake meandering, will be investigated in a more detailed manner in 225 the following section. In addition to this large scale motion excited by the turbine, there is a wide 226 range of small scales where the wake spectrum has higher energy in comparison to the incoming 227 flow. This points out that the turbine generates turbulence mostly associated with smaller scales. 228

Regarding the rough case, it is observed that the added energy is much smaller than the smooth 229 case and it is spread to all the scales. None of the distinct peaks are visible, including the turbine 230 frequency even in the very near wake. This is due to the fact that in this wind tunnel configuration 231 the wake behind a single turbine is extremely dissipative. The tip vortices cannot keep their integrity 232 even up to 1D. Additionally, the low frequency peak is not visible either. Two possible explanations 233 were given as to why the low frequency peaks were not visible for the rough case; either the large 234 scales in the incoming flow (dimensions around 1.5D) do not have the capability of triggering such 235 a phenomenon, or the wake itself is so dissipative that in-fact there is 'nothing to meander'. The 236 former one was extensively studied by Devinant et al. (2011). They observed that meandering is 237 very important when the incoming flow turbulence length scales are larger than the wake width. 238

Figure 14 concentrates on the three regions only in the very near wake,  $(x \le 1D)$ . Since every point measurement has one energy spectrum for each component, when all the spectra of one



Fig. 14 Frequency spectra of the streamwise velocity component for the inflow and the wake at 1D, for two different atmospheric conditions at three specific regions. The inflow **From left to right:** Smooth and rough cases. **From top to bottom:** Measurements at above tip, tip and below hub.

<sup>241</sup> component are gathered in a plot, it yields a contour. These contours for two different cases are <sup>242</sup> depicted in Figs. 15 and 16.

It is observed that for the smooth case in the near wake region the turbine's signature is visible. 243 However, it is worthwhile to mention that the blade passage frequency  $(3f_T)$  peak was not seen 244 in the results. Only the turbine rotational frequency  $(f_T)$  was detected, even though the sampling 245 frequency was sufficient to capture both. One reason for this can be the vortex wandering. From the 246 instantaneous particle image velocimetry (PIV) results, it was clearly seen that the vortices move up 247 and down, therefore it might be difficult to measure each of its signals with point measurements like 248 HWA. Another reason could be that due to the high rotational speeds, the rotor-motor mounting 249 becomes off-centred. Hence the blades themselves are moving up and down in addition to the 250 normal rotation. Either way, from the spectrogram this peak is only visible up to 2D. Afterwards 251 most of the energy in the small scales are shifted towards the large scales. The large scales persist 252 up to 11D where the last measurement location is. Overall, the far wake is dominated by large 253 scales and a full recovery towards the incoming flow is not visible up to the last measurement point. 254

For the rough case only 4 different downstream positions were considered, namely x/D = 1, 4, 7, 11 (see Fig. 15), since the other positions did not show distinctive changes. It is observed that the turbine effect is relatively less persistent. The cut-off filter characteristic is seen for the regions below hub up to 4D. In addition, the added energy levels are smeared across all the length scales, however, they are consistently lower in comparison to the smooth case. At the very far wake, where x/D = 11, the turbine signature is not visible at all.



Fig. 15 Differential energy spectra obtained from each point measurement at various downstream positions for rough case. The colour scale represents the inflow subtracted wake spectrum.

<sup>261</sup> 3.3 Meandering for Smooth Wall Case

In this part of the paper, the meandering was addressed through a set of experiments only under the smooth-wall boundary-layer conditions, where a distinct low frequency peak was detected during the spectral analysis. In order to ensure that the peak's existence was persistent, the experimental campaigns were carried out at various turbine operational conditions, namely tip-speed ratios and incoming hub-height wind speeds. A number of tip-speed ratios ranging from 4.9 to 7.5 and a number of velocities ranging from 4 m s<sup>-1</sup> to 12 m s<sup>-1</sup> were covered. The results show that (see Fig. 17) the rotor diameter based Strouhal number when non-dimensionalized with the hub-height wind speed remained on the order of 0.25. ( $St = f \cdot D / U_h$ )

This number is indeed in the order of bluff body vortex shedding. An experimental work on 270 vortex shedding behind cylinders under turbulent flow was carried out by Cheung and Melbourne 271 (1983). The data that is closest to the present study was the one with an ambient turbulence 272 intensity of 6.8% and a Reynolds number of 80,000, which yielded a Strouhal number of 0.25, 273 as was found here in this work. Also another study on bluff bodies with shear flow (Maull and 274 Young, 1973), show a similar Strouhal number when the centre-line velocity is used for the non-275 dimensionalization of frequency. On the other hand, the article (Medici and Alfredsson, 2006) in 276 which the meandering is linked to the bluff body vortex shedding shows a lower Strouhal number, i.e. 277  $St \approx 0.13$  which is in better agreement with a solid disc vortex shedding. With this output another 278 question was raised regarding the link between the meandering phenomenon and the contribution 279 of the wind turbine intrinsic behavior. 280



Fig. 16 Differential energy spectra obtained from each point measurement at various downstream positions for smooth-wall case. The colour scale represents the inflow subtracted wake spectrum.



Fig. 17 Strouhal number  $(f \cdot D / U_h)$  variation at various turbine running conditions

## 281 4 Summary

A wind-tunnel study was carried out with scaled three-bladed wind-turbine models under two different boundary-layer inflow conditions. Time-resolved measurements were obtained, covering 11D in the streamwise and 2.5D in the vertical direction. The emphasis was on the development of the streamwise velocity component and the spectral content.

The results were in agreement with the aforementioned previous works and flow physics. The 286 higher mixing rates caused by the high incoming turbulence, accelerates the wake recovery. While 287 this is an advantage for the downstream turbines from the wind speed point of view, the highly 288 fluctuating wind could result in an earlier failure of the turbine components in real life situations. 289 Therefore, the overall effect on the cost of energy can be non-beneficial. Relatively high turbulence 290 intensity levels were observed at the top-tip region, produced by the high velocity gradients. The 291 distinguishing feature of the turbulent shear stresses as well as the turbulence intensity spatial 292 distribution was that the peak values were reached much nearer to the turbine for the rough case. 293 This fits with the earlier wake recovery concept, since these are associated with the momentum 294 transfer from the higher momentum regions towards the wake centre. 295

Additionally, the spectral analysis yielded three regions in the near-wake where the turbine 296 has a different effect on the turbulent scales. As pointed out by Chamorro et al. (2012), this 297 can be a way to parametrize the turbine from a spectral perspective, that could eventually lead 298 to simpler wake models with higher accuracy and better physical understanding. Moreover the 299 specific low frequency peak, which was detected around the rotor region, was attributed to the 300 meandering phenomenon. Further investigation on this issue was carried out through a number of 301 test campaigns, by changing the tip-speed ratio (ranging from 4.9 to 7.5) and the incoming velocities 302 (ranging from  $4 \text{ m s}^{-1}$  to  $12 \text{ m s}^{-1}$ ). It was found that the rotor diameter based Strouhal number, 303 when non-dimensionalized with the hub-height wind speed, was unconditionally on the order of 304 0.25. This is an important outcome of this study. It is well known that certain contradictions exist 305 in the literature for association of bluff body dynamics to wind turbine wake meandering. However, 306 considering that many high-fidelity flow simulation outputs show persistent meandering deep in the 307 wind farms, where relatively smaller scale structures are present, it is likely that the continuation of 308 the meandering is provided via the intrinsic wind turbine behaviour. During this set of experiments 309 this behaviour was observed for single wind turbine model wake, under controlled wind conditions. 310

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