# The effect of the number of blades on wind turbine wake - a comparison between 2-and 3-bladed rotors



2016 J. Phys.: Conf. Ser. 753 032017

(http://iopscience.iop.org/1742-6596/753/3/032017)

# The effect of the number of blades on wind turbine wake – a comparison between 2-and 3-bladed rotors

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**Abstract**. Due to cost benefit and weight reduction, 2-bladed wind turbines have the potential to become more important for offshore wind applications. In order to optimize the arrangement of wind turbines in wind farms and for accurate forecasts of the power production, a detailed knowledge of the wake flow is needed. In this study, three different rotors with varying number of blades and similar performance behaviour have been designed and manufactured using the 3-dimensional (3D) printing technology. The performance characteristics of these rotors as well as their wake features are measured experimentally in wind tunnel tests and compared. The velocity deficit is seen to vary only insignificantly for the wakes in distances of 3D (where D is the rotor diameter), 5D and 7D behind the turbine. However, higher turbulence intensity levels are recorded in the wake of the 2-bladed rotors. This could have potential for a faster wake recovery and thus a narrower turbine spacing.

## 1. Introduction

In the wind power industry the development and research in the last decades focused mostly on 3-bladed turbines. Whereas in the 1970's and 1980's 2-bladed turbines were still investigated and considered in turbine development, the research effort in 2-bladed turbines was only minor in the last years. This is due to the disadvantages of 2-bladed rotors compared to 3-bladed rotors, such as the higher noise emissions, the distracting visual effects and the unfavorable dynamic behavior. However, as the offshore wind energy market is gaining importance, the 2-bladed turbines are getting more significant again. This is due to the fact, that the drawbacks are not so much relevant offshore and the big advantage of one less rotor is strongly decreasing the costs [1]. Nevertheless the maximum theoretical attainable performance is increasing with increasing blades number because of reduced tip vortices, which is also a drawback for 2-bladed rotors when comparing them to the established 3-bladed rotors. This fact should also be considered when looking at the economic potential of the rotor blade number. Moreover, in a wind farm set-up, wake effects are especially of interest to evaluate how the turbines interact and hence, their implication on wind farm design and power production.

There are several structural issues with wind turbines with 2-bladed rotor. One of the main issue is the unsteady loading of the blades. Whereas a 3-bladed rotor has a constant inertia about the yaw axis, which is independent of the azimuthal position of the rotor hub. However, the rotational inertia of a 2-bladed rotor is periodic, with the maximum at the horizontal position and the minimum at the vertical position and consequently, 2-bladed turbines have higher cyclic loads relative to 3-bladed rotor [2]. It is also unfavorable that when one blade is in the tower shadow the other one is pointing straight up and is thus exposed to the strongest winds under atmospheric inflow conditions. There are some strategies how to solve these problems and reduce the turbine loadings. However, the presented article will only focus on the aerodynamic performance and the wake effects of wind turbines with 2- and 3-bladed rotors.

The influence of the number of blades on the performance of a wind turbine was discussed by Wilson Lissaman and Walker in 1976 [3]. They showed that the power coefficient of a wind turbine approaches

Betz limit as number of blade increases. However, using a computational fluid dynamics (CFD) analysis, Newbauer and Kupathy obtained opposite results when they investigated 2-, 3- and 4- bladed rotors and observed an increasing power coefficient with decreasing number of blades [4]. The same trend was observed by Duquette, Swanson and Visser [5] who performed experimental and numerical studies on blade number effects, but only for three and more blades. McTavish, Feszty and Nitzche [6] looked at the wake expansion of a 2- and a 3- bladed turbine experimentally. However, they used two completely different turbine concepts and therefore their results are not suited for comparison of blade number effects. In a recent study, Newman, Cal and Castillo [7] investigated wake effects of a wind turbine arrangement with varying number of blades experimentally with particle image velocimetry (PIV). In their experiment, they identified the wakes of two 3 x 4 turbine arrangements adjusting the same power output, one array consisting only of 3- bladed and one only of 2- bladed turbines. They found velocity differences of up to 10% in the near wake and subtle distinctions in the far wake. Furthermore, they showed that 3-bladed turbines cause 25% higher fatigue loads than 2-bladed ones for the second turbine row.

The main objective of this present work is to show how rotors, with the same maximum power coefficient, but different number of blades influencing the wake characteristics of a wind turbine. The focus here is on the difference between 2- and 3- bladed rotors. As 2-bladed rotors are considered to become significant in offshore wind application, it is important to understand how turbines with such rotors affect one another in a wind farm arrangement. As turbines with 3-bladed rotors have been investigated closely in the past and a lot information about their wakes is available, the wakes of 2-bladed rotors are compared with those of a 3-bladed rotor to find the main distinctions between them. In addition, effect of number of blades on the inflow conditions and consequently the power output of a downstream turbine is presented. Furthermore, the turbulence characteristics of the wake are investigated to quantify wake recovery rates and the resulting fatigue loads on the downwind turbine.

## 2. Methods

### 2.1. *Experimental setup*

The experiments were conducted in a closed-return wind tunnel located at the Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway. The wind tunnel has a test section of 2.7m x 1.8m x 11.0m. The rotors were mounted on the model turbine as described in [8]. The blockage ratio of the turbine in the wind tunnel is 11.8% [9]. The wind tunnel was operated at low inlet turbulence intensity of 0.23% and the inlet velocity $U_\infty$ of 10.0m/s for all experiments. The torque was measured with a torque transducer installed inside the hub of the model wind turbine and the thrust force was measured with a 6-component force balance. The measurements with these devices resulted in uncertainties of about ±3% for the maximum power coefficient ($C_P$) and ±2% for the thrust coefficient ($C_T$) at the optimum tip speed ratio (TSR). A sketch of the experimental setup is shown in **Figure 1**.

Wake velocity measurements were carried out at downstream distances of 3D, 5D and 7D (where D is the rotor diameter) and at the wind turbines' hub-height. This distances where chosen to examine the wake development as well as the main wake features, which were expected to be significant at 3D, whereas distances of 5D and 7D are considered to be more relevant for full scale applications. Moreover, in order to get a clear understanding of the inflow conditions of the downstream turbine, full two-dimensional wake measurements for all three rotors were conducted at 5D. All the wake measurements were performed when the wind turbines were operating at their respective optimum tip speed ratio. The velocity measurements were conducted using a 2-component Laser Doppler velocimetry (LDV) instrument. The uncertainty of the mean velocities are lower than ±0.5% of the mean velocity considering a 95% confidence interval whereas the uncertainty of the turbulence intensities are calculated to be lower than ±2% of the mean velocity with a confidence level of 95%.

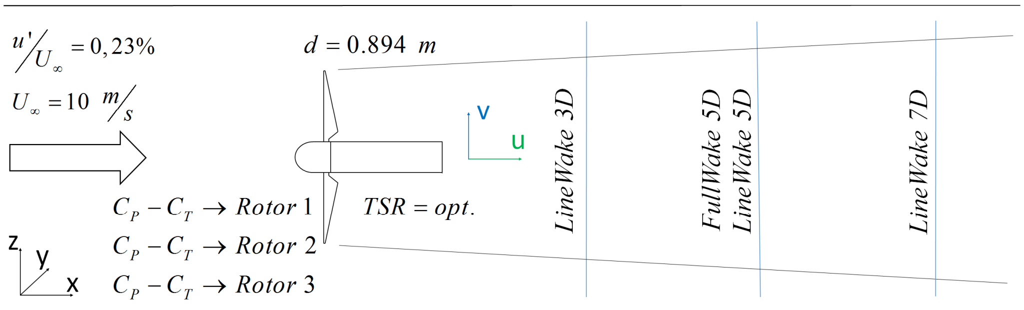


**Figure 1.** Sketch of the experimental setup.

### *2.2. Rotor design*

The rotor design is based on the rotor developed at the Department of Energy and Process Engineering (at NTNU Trondheim), which is described in [8] based on the NREL S826 airfoil. This rotor is a 3-bladed rotor milled from an aluminum alloy and it was used in the study as reference rotor. The purpose of the rotor design process is to produce 2-bladed rotors that have the same maximum power coefficients ($C_P$) as the reference rotor and design parameters, which are based on the 3-bladed rotor (NTNU rotor). When the number of blades is changed, other blade parameters are adjusted so the rotors would have similar performance behavior. The two main parameters which were adjusted in the blade design process in this study are the chord length and the twist angle. Consequently, two new rotors were designed, one with the same aspect ratio (rotor 2) and another one with the same solidity (rotor 1) as the reference rotor. The 2-bladed rotor with the same aspect ratio as the 3-bladed rotor needs to have a higher tip speed ratio (TSR) to achieve a similar $C_P$ as the 3-bladed rotor, which involved a change of the twist angle to take the higher circumferential velocities into account. The other 2-bladed rotor with the same solidity requires a modified chord length distribution to change the blocked area of the rotor and the TSR for this rotor concept was expected to be the same.

To stay as close as possible to the reference case, the twist angle distribution was related to that of the reference rotor. Thus, the twist angles where reduced proportionately to the original twist angle distribution. The performances of the resulting rotor were determined with a blade element momentum (BEM) code and compared the results to that of the reference rotor. The twist angles were adjusted until the same maximum $C_P$ value was achieved. For the rotor with the same solidity the reference chord length was multiplied by 1.5 to take the area of the one dropped blade into account. Calculations with the BEM code showed that the twist angle had to be also modified slightly for this rotor to reach the same maximum $C_P$ value as for the reference rotor. The resulted rotor properties of the three rotors, which were manufactured and used in the study are presented in **Table 1**. All rotors are rotating in clockwise direction.

**Table 1.** Properties of tested rotors.

| | Description | Chord length [%] | Twist angle [%] | Opt. TSR |
|---|---|---|---|---|
| Rotor 1 | 3-bladed rotor | 100 | 100 | 6 |
| Rotor 2 | 2-bladed rotor same aspect ratio | 100 | 70 | 7 |
| Rotor 3 | 2-bladed rotor same solidity | 150 | 95 | 6 |

All three rotors were manufactured using a 3D printer based on the multi-jet modeling technology. In a preliminary study, it was checked if this fabrication technique is suited to produce accurate blades that can be used in wind tunnel experiments. The results of this preliminary study showed that with the selected 3D printing technology, it is possible to produce blades with fine features in a high quality and with a good accuracy. Therefore, the printed blades are suited for the application in wind tunnel tests.

The three rotors, which were fabricated for the wind tunnel experiments for this article are depictured in **Figure 2**.


**Figure 2.** Printed rotors for experiment: (a) Rotor 1, (b) Rotor 2 and (c) Rotor 3.

*2.3. Rotor performance*

The purpose of the rotor design process was to match the maximum power coefficients of the three different rotor concepts. Therefore, preliminary calculations were undertaken using a BEM code. The results of these calculations showed that the maximum $C_P$ values were identical for the three designed rotors. In order to validate the results of the preliminary calculations, the power coefficient and thrust coefficient were determined experimentally as a function of TSR. **Figure 3** present the experimentally measured $C_P$ and $C_T$ profiles for the three rotor concepts. It can be seen, that the maximum $C_P$ values differ slightly, thus the predictions with the BEM code where not precise as the blades were designed to have exactly the same maximum $C_P$. In **Figure 3**, it can be seen that the two 2-bladed rotors have maximum values, which are slightly lower than that for the 3-bladed rotor. While rotor 1 (3-bladed rotor ) has the maximum $C_P$ of 0.480 at TSR 6, rotor 2 has a maximum $C_P$ of 0.452 at TSR 7 and rotor 3 has maximum $C_P$ of 0.453 at TSR 6. Consequently, the maximum $C_P$'s of Rotor 1 is 2.7% larger than the maximum $C_P$'s of rotor 2 and rotor 3.

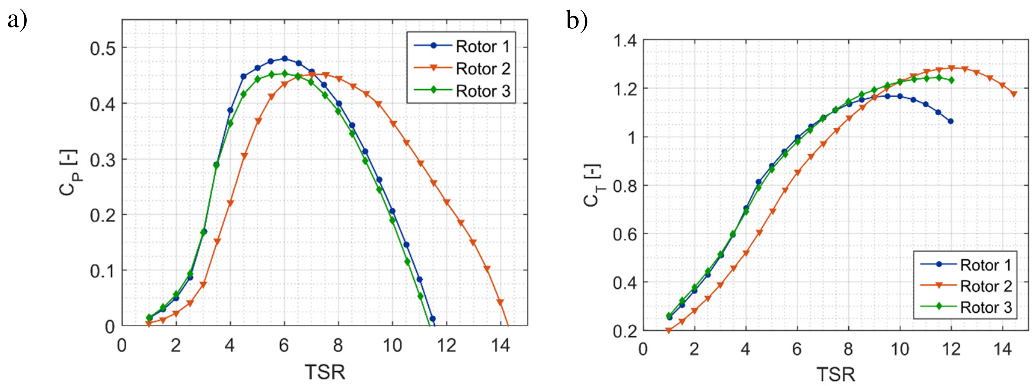


**Figure 3.** (a) Power coefficient and (b) thrust coefficient, as a function of the tip speed ratio for the three investigated rotors.

From Figure 3b, it can be observed that rotor 1 and rotor 3, which have the same solidity, have similar $C_T$ profiles for TSR $\leq$ 8, and thereafter, the two profiles are diverged. On the other hand, rotor 2 has a slightly lower $C_T$ which is on an average 18% lower when compared with the other two rotor concepts within the 1 <TSR < 8. From TSR> 8, the $C_T$ for rotor 2 is observed to continue increase whereas the

$C_T$ for the other two rotor concepts start to decrease. However, at the respective optimum TSR ($TSR_{max}$ = 6 for rotor 1 and rotor 3 and, $TSR_{max}$ = 7 for rotor 2), the $C_T$ values are very similar and all three lie in the range of 1.0.

## 3. Results and discussion

### *3.1. Kinetic energy in the wake*

The wake of a wind turbine is characterized by a velocity deficit and a higher turbulence level behind the turbine. The velocity deficit in the wake is important to know, as this gives information about the energy that is available for a wind turbine operating downstream and thus, in the wake of an upstream wind turbine. In the presented study the effects of blade number of a wind turbine rotor on the wake is investigated. Therefore, the wake velocities for the three different rotors concepts were measured at 3D, 5D and 7D behind the model turbine. At these distances line wakes at turbine hub height where measured in a wind tunnel width range of -2.57z/R to+ 2.57z/R (wind tunnel width (z) position divided by rotor radius (R), with an interval of 50 mm. The results of these measurements are shown in **Figure 4**. In this figure, the downstream velocity (u) is normalized by the inflow freestream velocity ($U_\infty$). It can be seen from this that the mean velocities differ slightly for the different rotors. Slight variations are observed mainly in the area directly behind the rotors, whereas in the boundary area of the wake the velocity deficit is mostly similar for all three rotors at the investigated distances. As the velocity in the wake relates to the available power for a downwind turbine, the measured velocities were integrated over the rotor area to estimate available power in the wake. Using this information, the rotors were compared according to the energy they left in the flow for a downwind rotor. However, for all the observations should be kept in mind, that the $C_P$ for rotor 1 is about 2.7% larger than the $C_P$ for the other two rotors at their maximum TSR.

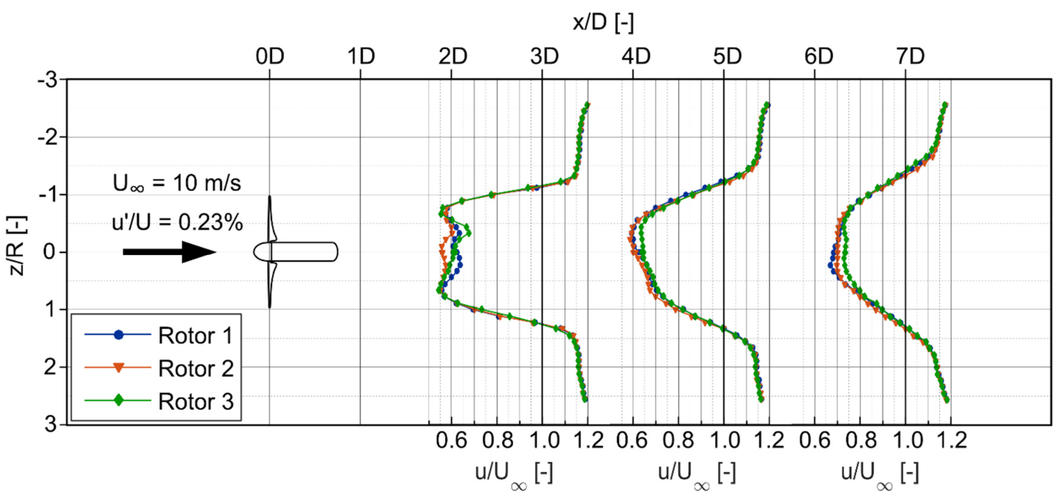


**Figure 4.** Velocity deficit in the wake for the three rotor concepts, normalized by the inflow velocity, at different downstream distances (3D, 5D and 7D) in the wind tunnel.

The estimated available power at downstream distance of 3D indicated that both the 2-bladed rotors have less energy in the wake compared with the 3-bladed rotor. However, the difference in the available power is not substantial, relatively to rotor 1, rotor 2 has 1.3% less available power in the wake and rotor 3 has only 0.2% less available power in the wake. At 5D, however, whereas rotor 2 has 1.1% less available power, rotor 3 has 3.2% more available power in the wake than rotor 1. The differences in

Journal of Physics: Conference Series **753** (2016) 032017 doi:10.1088/1742-6596/753/3/032017

kinetic energy for the three rotor concepts increases with increasing distance, thus the clearest distinctions can be observed at 7D. Accordingly at this distance the wake of rotor 2 has 1.1% less energy and rotor 3 has 3.2% more available energy in the wake than rotor 1. The trend that in the distinctions in the velocity deficit increases with increasing distance is obvious when comparing rotor 2 and rotor 3. Rotor 3 has always more energy in the wake than rotor 2, small difference of 1.1% at 3D but 4.0% at 5D and 4.3% at 7D. However, the differences in the velocities in the wake of the three rotors is insignificant and the velocity profiles are alike. Thus, it can be assumed, that an aligned arrangement consisting of two 3-bladed rotors has the potential to be more efficient compared with a similar turbine arrangement using rotor 2 and rotor 3, because the $C_P$ of rotor 1 is 2.7% larger.

To examine how the wake is changing with increasing distance the wake recovery rate is calculated. This is done by dividing the percentage change in available energy for the different downstream distances by the rotor diameter. Between 3D and 5D it is clear that rotor 3 with 7.7 %/D has the highest recovery rate whereas rotor 1 with 6.1 %/D and rotor 2 with 6.3 %/D having similar recovery rates. This trend cannot be seen for the recovery rates between 5D and 7D, where rotor 1, rotor 2 and rotor 3 have similar recovery rate of 5.4 %/D, 5.3 %/D and 5.5 %/D, respectively. Therefore, it becomes obvious that the wakes for all three rotors recover faster for the closer distances than in the region further down of the rotor.

The velocity profiles at the hub-height are very alike and thus, the difference in the wake kinetic energy fields at turbine hub height are obscured. To check if the distinctions are minor across the entire height of the rotors and check for asymmetry effects for the different rotors, full two-dimensional wake for the three rotors were measured at a distance of 5D in a width range from -1.5z/R to 1.5 z/R and height range from -1.5y/R to 1.5 y/R with an increment of 75 mm in y-direction and z-direction. The results of the full-wake measurement for the kinetic energy is shown in **Figure 5**.

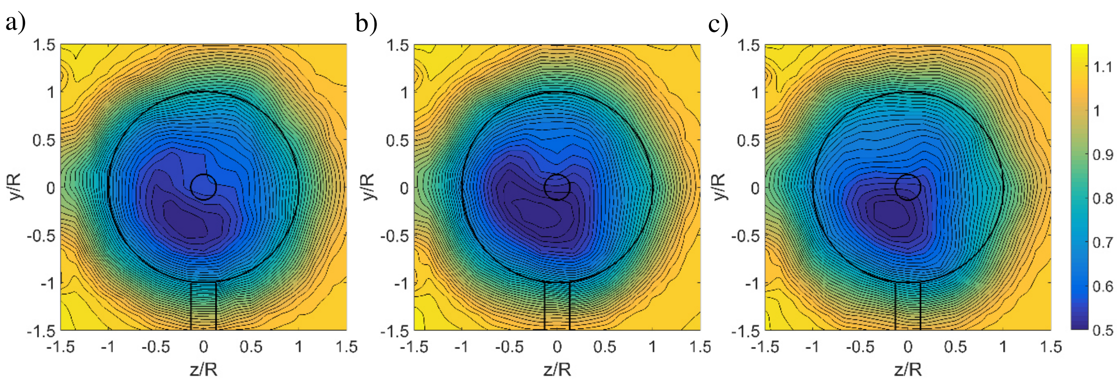


**Figure 5.** Contour plots for velocity deficit in the wake, normalized by the inflow velocity, at downstream distance 5D: (a) rotor 1, (b) rotor 2 and (c) rotor 3. (The thick black line represent the turbine rotor outline, looking in flow direction)

Looking at the contour plots it can be observed that for all three rotors the wake maximum velocity deficit is displaced below hub height and shifted to negative y- and z- half plane. In addition, on the outer edges of the rotors it can be observed that the wake is shifted towards the negative z-direction. This asymmetry effects are expected, which is due to tower interactions with the wake as show by Pirella [10]. However, it can be seen that this maximum velocity deficits change slightly for the three rotors. Whereas for rotor 2, the area with the high deficits is largest but it is slightly smaller for rotor 1 and rotor 3. When comparing the available energy at the rotor plane similarly as for the line wakes the same trends become obvious at a distance of 5D. Here, rotor 1 has 0.8% more energy than rotor 2 with difference of 0.2% compared to the line wakes. The energy difference between rotor 1 and rotor 3 shows 2.6% more energy for rotor 3 almost the same results as for the line wakes. Larger differences can be observed when looking at the share of energy on left-side of the wake than the right-side. For the energy calculations based on the full wakes, the theoretical power is around 10% lower than the theoretical power calculation based on the wake profiles at the hub-height. Consequently, the analysis based on the line wakes the power in the wake is somewhat underestimated. However, the results show, that there are no major differences in the kinetic energy in the wake at 5D for the three rotor concepts in altitudinal direction.

To examine where the 3- and 2-bladed rotor concepts diverge from each other, the energy density at every measurement point was calculated for all three rotor concepts and the energy densities of the 2-bladed rotors were subtracted from the energy density of the 3-bladed rotor. The results of these calculations are shown in **Figure 6**. This figure show that the major differences in energy density between the 2- and 3-bladed rotors occur in the area outside of the rotor where they are up to -20% in positive z-direction and +20% in negative z-direction. Within, the rotor area of the turbine the distinctions are only minor, where the differences from rotor 1 and rotor 2 are in the area between -5 and 5% while the differences from rotor 1 and rotor 3 are between -9 and 3%. However, it can be seen that rotor 1 has a higher energy density in its wake at 5D as rotor 2, considering the rotor area of a potential downwind turbine. Rotor 3, on the other side, has a higher energy density in the wake as rotor 1 considering the same observation area. Moreover, the larger differences can be observed in the outer part of the wake, here the 3-bladed rotor has a higher energy density as both 2-bladed rotors in negative z-direction and vice versa in positive z-direction. This is due to the differential symmetry behavior for the different blade number of the rotors.

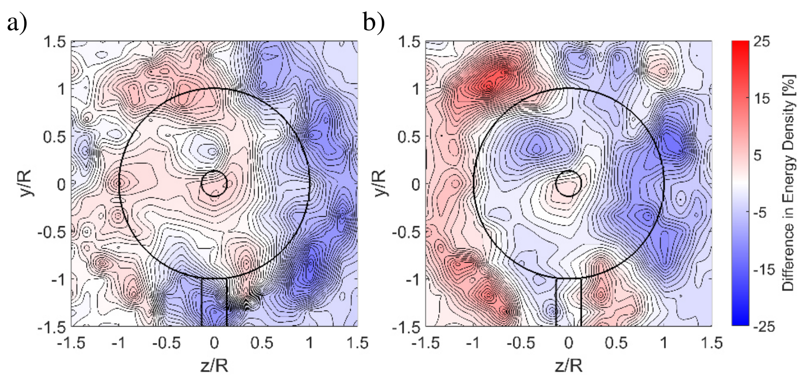


**Figure 6.** Difference in energy density in the wake in share of theoretical power at 0D, at downstream distance 5D in y- and z-direction normalized by the rotor radius( looking in main flow direction): ( a) rotor 1 – rotor 2 and (b) rotor 1 – rotor 3.

### *3.2. Turbulence intensity in the wake*

The second wake feature which is of interest is the turbulence intensity and thus, the turbulent energy in the wake. As the LDV measurement system measures velocities in 2 directions the combined turbulence intensity for the x- and z-direction was calculated according to equation (1).

$$TI = \frac{\sqrt{\frac{1}{2}(u_x'^2 + u_z'^2)}}{\sqrt{U_{\infty,x}^2 + U_{\infty,z}^2}} * 100 \quad [\%] \tag{1}$$

**Figure 7** shows that the turbulence intensities obtained from 2 directional components at the distances 3D, 5D and 7D, have significant variations among the three sets of rotors considered in this study. These differences occurring mostly in the area behind the rotor and at the turbine rotor edge where the intensity peaks occur. In the outer wake region, the three wakes are almost identical. When comparing the rotor concepts, the 2-bladed rotors produce higher turbulence in the wake at all three distances investigated. At a distance of 3D the integral of the turbulence intensity of the investigated wake section is 0.5% higher in the wake of rotor 2 as those of rotor 1 and rotor 3 has even a 2.0% higher overall turbulence intensity as rotor 1. At the distance of 5D, the same trend can be observed, the difference between rotor 3 and rotor 1 is only 1.2%. Even though the total turbulent energy in the measured section of the wake is only changing marginally at all three investigated distances, the differences in turbulent energy between the three rotor concepts are decreases with increasing distance. This is due to the fact that the overall turbulence intensity increased by around 1% between 3D and 7D for rotor 1 and rotor 3 whereas it decreased by 0.5% in the same section for rotor 3. Consequently, at the downstream distance of 7D, the differences for the three rotors are only minor and in the range of 0.2%. The profiles in the diagram in **Figure 7** at 7D are almost overlapped in the outer part of the wake as well as in the area behind the rotor. Furthermore, the turbulent intensity profiles even out with increasing distance. Whereas at the distance of 3D the turbulent intensity profiles have high peak values between 17 and 22% at the rotor edge and peak values of up to 10% at the inner rotor area. These extreme values reduce with increasing distance due to turbulent mixing within the wake. Consequently, at 7D the turbulence intensity varies approximately 2% between the center (10%) and the rotor edge (12%).

The higher turbulence levels at distances at 3D and 5D indicate that the wake of the 2-bladed rotors recovers faster in that area. This becomes obvious especially when looking at rotor 3 that has the highest turbulent levels. The faster wake recovery rate was already observed in the kinetic energy analysis where the wake of the 2-bladed rotors especially for rotor 3, recovered faster than the wake formed behind the 3-bladed rotor. The higher turbulence levels can be beneficial in a wind farm arrangement as the wakes, especially at low distances of separation, recover faster, the turbine spacing can be reduced and thus, more wind turbines can be installed in a smaller area. This can reduce the total land rental fee costs and increase the wind farm energy yield per unit area of land. However, the fatigue loads on a turbine operating in the wake of a 2-bladed turbine are increased due to the higher turbulence level.

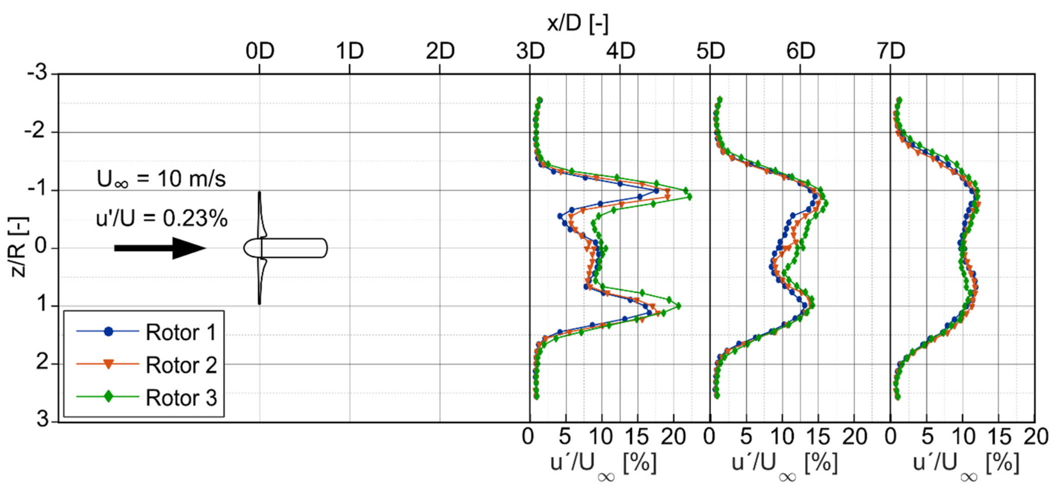


**Figure 7.** Wake turbulent energy obtained from 2 directional components for the three rotor concepts, at different downstream distances (3D, 5D and 7D) in the wind tunnel.

In order to examine how the turbulent energy differs across within swept area of the wind turbine and to investigate the asymmetry effects for the different rotors, the turbulence intensity was measured in full two-dimensional for the three rotors at a distance of 5D within a width range of -1.5z/R to 1.5z/R and a height range of -1.5y/R to 1.5y/R with an interval of 75mm along both directions. **Figure 8** shows the contour plots for the turbulent intensity obtained from the x- and the z-direction. The 2-dimensional wakes confirm the observations made from the line wakes. It can be clearly seen, that the 2-bladed rotors (Figure 8b,c) have higher turbulent levels than the 3-bladed rotor (Figure 8a) and especially, the rotor 3 shows very high turbulence intensity (Figure 8c). The contour plots show clearly that the intensity peaks are at the edge of the rotors, which indicates that the largest turbulence is induced by the tip vortices.

Consequently, the 2-bladed rotors generating stronger tip vortices than the 3-bladed rotors. Furthermore, the wakes of all three rotors are slightly shifted towards positive z-direction whereas this effect is more obvious for the 2-bladed turbines and especially rotor 3. In addition, the maxima of turbulent intensity for all three rotors occur at the rotor edge at the positive z- and negative y half. This is opposite to the asymmetry observed for the wake velocities where the highest deficit was at the negative z- and y-direction. Nevertheless, this asymmetry is expected to be caused by interferences of the wake with the turbine tower. The evaluation of the turbulence intensity in y- and z- direction reinforce the observations made from the turbulent intensity profiles at hub-height of the rotor and thus, the higher turbulence of the 2- bladed rotor concepts especially in the tip region.

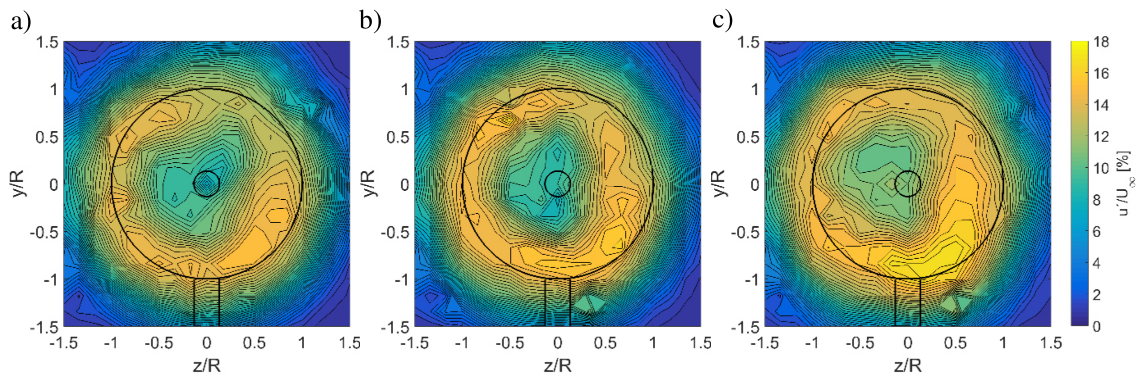


**Figure 8.** Contour plots for turbulent intensity obtained from 2 directional components, at downstream distance 5D (looking in flow direction): (a) rotor 1, (b) rotor 2 and (c) rotor 3.

## 4. Conclusions

The comparison between the wakes of one 3- bladed and two 2-bladed rotor concepts with similar maximum $C_P$ values have been presented and discussed in this paper. The results show that the wakes formed behind rotors with different blade number are have minor distinctions and the thrust force acting on the rotors is similar for the optimal operation range of the rotors.

The velocity deficit in the wake formed behind the three different rotors is offers no major deviations between the tested rotors. Thus, from a power optimization point of view, the mean wake velocities provide only a minor potential for improvement. Consequently, it can be concluded that the number of blades is not influencing the velocity deficit in wake and thus, the potential inflow velocities of a downwind turbine strongly. Nevertheless, in future investigations it would be of interest to test turbines with rotors with varying blade number in an experiment with an aligned turbine array to confirm the observations made by investigating the wakes and if there is a possible potential for improvement by adjusting control strategies.

However, the turbulent intensities show higher variation for the 2-bladed rotors. Especially at the tip region, the turbulent intensities are higher, which is caused by the stronger tip vortices generated of the 2- bladed turbines. This higher turbulence levels in the wake support a higher wake recovery rate of the 2- bladed rotors when compared with the 3- bladed rotor, especially in closer distance behind the turbine. This faster wake recovery offers the potential for a narrower turbine spacing and thus a higher power density per unit land area in a wind farm plant. However, from a structural point of view, the downstream turbine operating in the wake of a 2-bladed turbine experiences higher turbulence levels, which could increase fatigue loads.

## References

[1] Hau, E. and H. von Renouard, *Wind Turbines: Fundamentals, Technologies, Application, Economics*. 2013: Springer Berlin Heidelberg.
[2] Jamieson, P., *Innovation in wind turbine design*. 2011: John Wiley & Sons.

[3] Wilson, R.E., P.B. Lissaman, and S.N. Walker, *Aerodynamic performance of wind turbines*. 1976, Oregon State Univ., Corvallis (USA).

[4] Newbauer, S. and S. Kumpaty. *Computational Fluid Dynamics of Aerodynamic Effects for Optimum Number of Wind Turbine Blades*. in *ASME 2012 International Mechanical Engineering Congress and Exposition*. 2012. American Society of Mechanical Engineers.

[5] Duquette, M.M., J. Swanson, and K.D. Visser, *Solidity and blade number effects on a fixed pitch, 50 W horizontal axis wind turbine.* Wind Engineering, 2003. **27**(4): p. 299-316.

[6] McTavish, S., D. Feszty, and F. Nitzsche, *Evaluating Reynolds number effects in small-scale wind turbine experiments.* Journal of Wind Engineering and Industrial Aerodynamics, 2013. **120**: p. 81-90.

[7] Newman, A.J., R.B. Cal, and L. Castillo, *Blade number effects in a scaled down wind farm.* Renewable Energy, 2015. **81**: p. 472-481.

[8] Krogstad, P.Å. and J. Lund, *An experimental and numerical study of the performance of a model turbine.* Wind Energy, 2012. **15**(3): p. 443-457.

[9] Adaramola, M.S. and P.A. Krogstad, *Experimental investigation of wake effects on wind turbine performance.* Renewable Energy, 2011. **36**(8): p. 2078-2086.

[10] Pierella, F., *Experimental Investigation of Wind Turbine Wakes and Their Interaction.* 2014.