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Wakes and wake interaction between rotors and discs in an experimental model array

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Abstract. The aim of the present paper is to obtain a better understanding of wakes generated by 2, 3 and 4 elements (disks and/or rotors) modeling an array of wind turbines in a wind farm. We here extend the results from our previous experimental model studies on the correlation between the behavior of the wake behind dual configurations of passive disks and active rotors to establish new knowledge regarding the wake development behind the 3rd and 4th rotor operating in a wake. To accomplish this, 2D PIV velocity measurements were carried out to investigate the flow properties upstream and downstream the tested rotors and discs in the array. The study also provides measured values of power and thrust coefficients of the model turbines using strain gauges installed directly on the rotors. The aim of the laboratory experiment is to provide data to calibrate and validate wake models for design and analysis arrays of wind turbines located in wind farms.

1. Introduction

In wind farms, the optimization of operating conditions requires more studies when several wind turbines are located after each other in an array [1-4]. Measurements of the power characteristics [1] in wind-turbine arrays have shown that the power at the second turbine decreases strongly as compared to the power of the first frontal one, after which the power again increases for the third turbine and then stabilizes after the fourth wind. The deviation from the optimum operation mode of the next turbines in the array is usually associated with their reduced performance due to the wake from the previous one, which reduces wind speed and increases turbulent pulsations of the incoming flow [5-7]. However, the effect of power stabilization needs to be studied and further explained.

This vortex wakes and vortex structures behind different single and dual configurations of disks and/or rotors modeling the wind turbines were the subject of our previous laboratory tests [7-12]. At first, our experiments [8-11] indicated that any single or dual disk system cannot satisfactorily replace the same system with rotors when analyzing wake properties behind them. Next, it was found, as an overall conclusion in [12], that discs can be used to replace rotors when carrying out laboratory tests of wind-farm models, but they should not be located just upstream of the rotor being investigated. Hence, testing e.g. the 3rd rotor in an array, a disk-rotor configuration will work, whereas disk-disk or rotor-disk configurations will not. Using this as a general rule permits us in the current investigation to expand the setup to comprise arrays of 2, 3 and 4 rotors in our laboratory model of rotor arrays.

The overall aim of the work is to determine wake properties and the power development in a model array of wind turbines, in order to reproduce and explain the effect of power stabilization to optimize and validate numerical models for flow simulations of wind farms.
2. Experimental setup and experimental methods
The experiments were carried out in a water flume where velocity fields and powers were determined for the 2nd, 3rd or 4th rotor in an array from two to four elements located coaxially (Fig. 1). The water flume has a length of 35 m, a width of 3 m and the operative height of 0.9 m. A long test section with 3-m transparent walls was installed at a distance of 20 m from the flume inlet; walls and bottom of the test section were made from glass of optical resolution.

A set of three-bladed rotor of diameter $2R = 0.376$ m and blades length 0.159 m, designed using CD7003 blade profiles, was specially manufactured and designed using Glauert’s rotor theory [13] for optimal wind turbines with tip speed ratio (TSR) $\lambda = 5$, where $\lambda = \Omega R/U_0$, $\Omega$ is angular speed of the rotor and $U_0 = 0.6$ m/s is the velocity of free flow. The rotors were driven by a JVL Industri Elektronik MAC400 servo motor which was operated at a constant rotational speed. The software “MacTalk”, which was used to control the motor, ensured a rotor RPM within 2 % accuracy.

The model arrays of 2, 3 and 4 elements contain different configurations of disk and rotor: rotor (R) rotor-rotor (R-R); disk-rotor-rotor (D-R-R) and disc-rotor-disc-rotor (D-R-D-R). Examples of D-R-R and D-R-D-R from the considered configurations are shown in figures 2 and 3. Elements were located at equal distances of three to seven rotor diameters, $L_x = 3D$, 4D, 5D, 6D, 7D, corresponding to a typical range of locations of wind turbines in a wind farm. The current configurations were chosen due to previous studies that showed that the velocity deficit and flow oscillations in the wake behind the disk-rotor system is identical to the rotor-rotor system [12]. It was concluded based on these previous data that the mentioned configurations should produce identical wakes behind the last element as in the arrays with the rotors only (R, R-R, R-R-R, and R-R-R-R).

![Figure 1. Schematics of the measurement setup and testing array.](image-url)
The Reynolds number for all experiments was about 200,000. The level of turbulent pulsations (≈ 2%) for the undisturbed flow in the test section was measured in previous experiments for a single wind turbine model [14]. To investigate the influence of the turbulence on the arrays, a grid was installed upstream in water flume (Fig. 1 and 3). The turbulence intensity behind the turbulent grid was measured via the PIV system. The turbulence intensity behind the turbulent grid at distances from 0 to 3 rotor diameters was about 20%. The turbulent intensity at a distance from 3 to 5 rotor diameters was about 15%. At a distance from 5 to 10 rotor diameters, the turbulence intensity was decreased to 10%. Finally, it was decided to place the turbulent grid at a distance from 5 to 10 rotor diameters from the first element in the chain, resulting in a turbulent intensity of about 10%.

The velocity deficit was studied by velocity fields downstream to the last rotor in the array (Fig. 1). The velocity fields were measured by the Dantec 2D PIV system which gives two velocity components throughout a window of the light sheet. An Nd:YAG laser was used as a light source with the following characteristics: 120 mJ of energy in a single pulse, the wavelength 532 nm, operation frequency 15 Hz. The 2 mm thick light sheet was sent vertically into the channel from the bottom at the rotor axis. The images were recorded by two Dantec HiSense II cameras with 1344 ÷ 1024 pixels resolution. The velocity field was calculated using Dantec Dynamic Studio 2.21. The camera was placed perpendicularly to the flume wall (Fig. 1). The PIV system was calibrated using a target with a well-defined dot-pattern, which was translated and registered by the camera at the light sheet.

The image recording frequency for the PIV measurements was 15 Hz. The area of the PIV study of the wakes was divided into 12 separate windows. The measurement windows were 462x350 mm with 40 mm overlapping along flow direction to ensure to cover the entire velocity field. The choice of the position and size of the windows were based on previous visualization results [8-14]. The interrogation area covered 32x32 pixels with 25% overlapping, providing a spatial resolution of the velocity field of 5 mm. The planar PIV system was immobile while the systems of disk-rotor with fixed Lx installed on the movable platform was shifted along flume and then fixed to measure in the new measuring window. For each measuring window, the ultimate velocity field was obtained by averaging of 200 realizations. The measuring error of PIV was at the level of 3÷5% [14]. The final size of the total 2D velocity field was 2.94 x 0.35 m in longitudinal section and was performed by a combination of the calculated velocity field from each window (1F – 7F) excluding overlap zones for minimizing boundary errors.

The power and thrust coefficients were examined by measurements of the rotor torque and thrust, which were collected by strain gauges installed in the rotor mounting [4, 10, 14]. The torque of the motor was transferred to the rotor axis via a rigid gear transmission. The voltage of the sensors was amplified by a preamplifier, Scout 55, produced by Hootinger Baldwin Messtechnik, and was digitized by the ADC produced by National Instruments Company (Fig 1). Both strain sensors were calibrated with an inaccuracy of less than one percent using reference weights. The measured data served to
calculate the average torque and thrust values of the tested rotor. The electrical signal of the strain gauge sensors was recorded with a frequency of 125 Hz for 120 s.

3. Results

Figure 4 shows examples of mean velocity fields for different array configurations with a distance of 5 rotor diameters between the elements, where rotors operate at optimal $\lambda = 5$.

![Velocity Fields](image)

**Figure 4.** Examples of velocity fields for different configurations of arrays for distances between elements of 5 rotor diameters. The measurements are taken behind the last rotor.

The velocity fields are measured behind the last rotor. The data indicate a similar behavior of the wake structure behind the 2nd, 3rd, and 4th elements. These wake behaviors predict the effect of the power stabilization for the turbines in the arrays beginning from the 3rd element, which were found under actual wind-farm operations [1]. It is possible to see, that axial velocity near the rotor axis was equal: $U/U_0 = 0.27, 0.57, 0.61$ and $0.58$ at $x/D=3$; $U/U_0 = 0.51, 0.68, 0.69$ and $0.72$ at $x/D=5$ and $U/U_0 = 0.68, 0.75, 0.76$ and $0.76$ at $x/D=7$, for configuration with single, two, three and four elements.
respectively. The same wake behavior was presented also for other investigated distance between elements (Lx=3 D, 4D, 6D and 7D). For confirmation, this effect of velocity stabilization behind second and other elements the power and thrust coefficients were examined by measurements in these configurations.

In the next step of the investigation, the influence of different turbulent intensities of the incoming flow on the rotor performance was examined. The rotor was placed at a distance of about 5 rotor diameters from the turbulent grid, where the turbulence level was about 10%. Power and thrust coefficients were measured and compared for a single rotor with and without upstream turbulence. The force measurements were made at the same rotational speed of the rotor both with and without the turbulent grid. In table 1, measured values are shown for different tip speed ratios. The data show a small increase of the forces in the case with a turbulence grid, which however is rather limited. Hence, we may conclude that turbulence intensities up to 10% have an insignificant effect (about 1-2%) on the resulting thrust and power production. However, it may well be that grid turbulence in itself is not sufficient for reproducing the correct influence of the atmospheric turbulence.

Table 1. Power and thrust coefficients for a single rotor with and without upstream turbulence grid

| λ   | F, Hz | C_p without turbulent grid | C_T without turbulent grid | C_p with turbulent grid | C_T with turbulent grid |
|-----|-------|----------------------------|---------------------------|------------------------|------------------------|
| 4   | 1.98  | 0.22                       | 0.77                      | 0.22                   | 0.79                   |
| 5   | 2.48  | 0.40                       | 0.92                      | 0.41                   | 0.96                   |
| 6   | 2.97  | 0.40                       | 0.98                      | 0.42                   | 1.02                   |
| 7   | 3.47  | 0.37                       | 1.02                      | 0.38                   | 1.05                   |
| 8   | 3.96  | 0.32                       | 1.05                      | 0.33                   | 1.08                   |

The issue of the influence of the effect of turbulence on the electricity production and mechanical loadings of individual and clustered wind turbines were discussed in [15], with the conclusion was that it deserves to be studied much further. Our results contribute partly to this, but should certainly be supplemented with studies on more realistic turbulent conditions, corresponding to those encountered in practice.

Figure 5 shows the measurements of power coefficients for the model array. Indeed, the power of the second element strongly decreases and then the power is restored to a stable value for the next (third) rotor. In your experiments we have direct measurements $C_p$ and $C_T$ for 1-3 rotor and extrapolation for 4 and 5 elements, assumed that velocity field and velocity deficit have approximately same value behind 3 and 4 elements configuration. The observations in [1] of the operation of a real wind farm is partially confirmed. Also, we can conclude that the distances between the rotors in the array are important. Our data do not contradict the traditional concepts of the effects in the arrays of wind turbines. However, more research is required to elucidate the influence of atmospheric turbulence.

Conclusions
Our laboratory measurements of the power characteristics and velocity fields showed that for an array of wind turbines, the wakes stabilize for all rotors downstream the 2nd one in the array from which we conclude and explain the stabilization effect of the power characteristics. This experiment made it possible to predict their behavior for only for 5 elements; in the future, a larger number of elements in the array will be studied.

The influence of turbulence on the performance of wind turbines was found to be insignificant (about 1-2%) for grid-generated turbulence intensities up to 10%. The measurements need to be supplemented by further investigations, in particular regarding higher turbulence levels and turbulence.
properties corresponding to those encountered in the field. However, the present measurements may be of great value for validating computing codes for simulating wind farms, and we invite researchers in this field to use the data to validate their numerical tools.

![Graphs showing relative power coefficients of the rotors modeling wind turbines](image)

Figure 5. Relative power coefficients of the rotors modeling wind turbines with the different positions in the array and different distances between them Lx, for the tip speed ratio at $\lambda_1 = 4, 5$ and 7 with and without the turbulent grid. In all values related to the coefficient, $C_{P0} = 0.4$ of the frontal rotor at the optimal regime $\lambda_1 = 5$.

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References

[1] Nygaard N G 2014 J. Phys.: Conf. Ser. 524 012162
[2] Subramanian B, Chokani N and Abhari R S 2015 Renewable Energy 85 454-463
[3] Adaramola M S and Krogstad P-Å 2011 Renewable Energy 36 2078–2086
[4] Okulov V L, Mikkelsen R F, Sørensen J N Naumov I V and Tsoy M A 2017 J. Energy Resources Technology 139(5) 051210
[5] Bartl J, Pierella F, and Sætran L 2012 Energy Procedia 24 305-312
[6] Breton S P, Nilsson K, Olivares-Espinosa H, Masson C, Dufresne L and Ivanell S 2014 Renewable Energy 70 153-163
[7] Okulov V L 2018 Thermophysics and Aeromechanics 25(1) 1-20
[8] Okulov V L, Naumov I V, Mikkelsen R F and Sørensen J N 2015 J. Phys.: Conf. Ser. 625 012011.
[9] Naumov I V, Mikkelsen R F, Okulov V L and Sørensen J N 2014 *J. Phys.: Conf. Ser.* **524**(1) 012168
[10] Okulov V L, Mikkelsen R F, Naumov I V, Litvinov I V, Gesheva E and Sørensen J N 2016 *J. Phys.: Conf. Ser.* **753** 032060.
[11] Okulov V L, Litvinov I V, Mikkelsen R F, Naumov I V and Sørensen J N 2017 *J. Phys.: Conf. Ser.* **854** 012035.
[12] Sørensen J N, Robert F M, Kabardin I K, Litvinov I V, Naumov I V and Okulov V L 2018 *J. Phys.: Conf. Ser.* **1037**(7) 072045
[13] Sørensen J N, Okulov V L, Mikkelsen R F, Litvinov I V and Naumov I V 2016 *J. Phys.: Conf. Ser.* **753** 022020
[14] Okulov V L, Naumov I V, Mikkelsen R F, Kabardin I K and Sørensen J N 2014 *J. Fluid Mech.* **747** 369-380
[15] Brand A J, Peinke J and Mann J 2011 *J. Phys.: Conf. Ser.* **318**(7) 072005