Global blockage effects in wind farms

A Segalini\textsuperscript{1} and J-Å Dahlberg\textsuperscript{2} \\
\textsuperscript{1} STandUP for Wind, KTH Mechanics, Royal Institute of Technology, Stockholm, Sweden \\
\textsuperscript{2} Vattenfall Vindkraft AB, Stockholm, Sweden \\
E-mail: segalini@mech.kth.se

Abstract. An experimental and numerical study of wind-farm blockage has been performed to quantify the velocity reduction that the first row of a wind farm experiences due to other turbines downstream. In the present study, an attempt is made to demonstrate the existence of a two-way coupling between individual turbines and wind farm. Several staggered layouts were tested in the wind-tunnel experiments by changing the spacing between rows, spacing between the turbines in the same row and the amount of wind turbines involved. Three turbines located in the first row were monitored to assess their sensitivity to the turbines downstream. One of the experiments was replicated by means of numerical simulations performed in ORFEUS, a linearised code developed at KTH, in order to complement the experimental results. Simulations were performed at the same thrust coefficient and with a more distant ceiling to assess the eventual interference of the ceiling on the experimental results. Additionally, simulations performed at different thrust coefficients were done to assess its effect on the blockage phenomenon.

1. Introduction

The growth of wind energy in the recent years has led to an intense planning of wind turbines and wind farms, namely cluster of wind turbines to increase the power density, defined as the amount of power extracted per unit land/sea used. As wind turbines extract kinetic energy from the wind, it is generally expected that turbines placed downstream will produce less than those facing directly the wind. In order to account for wake effects, wake models were developed \cite{1, 2, 3} where prescribed wake deficits are imposed downstream of the turbines. These models are based on integral balances or energy arguments and introduce empirical parameters and formulas that have to be obtained from field data: the selection of these parameters represents one of the bottlenecks of the wake-model approach and provides uncertainties that can be quite large \cite{4}. In light of the fact that wake effects and wake interactions are still a big source of uncertainty, most of the researchers and practitioners in the wind-energy community have tacitly assumed that the first row of wind turbines facing the wind experiences a “free stream” wind condition and is therefore used as a reference to normalise the power of the turbines downstream to obtain, for instance, the array efficiency.

The upstream effect of a single isolated wind turbine is already accounted in the actuator-disk theory and a formula for the decrease of the velocity was reported by Koning \cite{5} by means of a linearised approach: the results indicate that the presence of a turbine is perceived upstream of it up to 2 turbines diameters ($2D$) and negligible farther upstream. Therefore, the current IEC standard \cite{6} recommends to place the mast to monitor the free-stream velocity between $2D$ and
4D upstream of the first row of turbines. All these considerations concern a single isolated wind turbine. Since the distance between rows in a farm is usually larger than 4D, it is expected that the turbines downstream should not affect the upstream turbines (a “wake-only” view following the notation of Bleeg et al. [7]). Since many wind-farm assessments were and are still performed with wake models, any upstream effect is invisible. Therefore, this perception that only wakes influence the farm became part of the general understanding of wind farms.

The experiments performed by Dahlberg and Hägglund in the Gävle wind tunnel [8], and the model developed by Ebenhoch et al. [9] and Segalini [10], indicated however that the assumption that the first row is unaffected by the rest of the farm is incorrect. From [8] it was evident that a distance of at least 30D is necessary to practically eliminate upstream effects of the farm blockage. The recent work of Bleeg et al. [7] investigated the blockage effect in three onshore wind farms (where several upstream masts were available near and far from the farm) and velocity differences were again observed depending on the relative mast position with respect to the farm. Numerical simulations with the actuator-disk method were performed showing good agreement with the observed velocity reductions, ruling out the possibility that blockage effects were a result of an experimental error. Now, since most of the farm-efficiency assessments are based on the production of the first row, it is clear that, if the first row is affected by global blockage due to the presence of the farm, this will influence not only the first row but all the turbines downstream. Several companies have therefore initiated research to quantify and assess global blockage effects, introducing this phenomenon as a new type of “farm loss”.

The present work reports results from an experimental campaign aimed at reproducing the experiments performed in the Gävle wind tunnel [8] together with a comparison with numerical results obtained with the code ORFEUS developed at KTH to complement the experimental data. This code has already been used to characterise upstream effects [10] by considering the velocity deceleration upstream of the farm, but here the simulations are performed considering different distances between the first row of turbines and the rest of the farm was changed, mimicking what was done in the new KTH experiments. The present paper is structured as follows. Section 2 reports details about the experimental setup, while the numerical setup is described in section 3. Section 4 shows some data analysis and reports evidence of blockage effects for all the investigated cases. Finally, section 5 reports the key findings of the work and some relevant discussions.

2. Experimental setup

The experiments were performed in the Minimum Turbulence Level (MTL) wind tunnel at KTH Royal Institute of Technology in Stockholm. The facility is a closed loop one with a closed test section 7 m long, 1.2 m wide and 0.8 m high. The inflow was nearly with constant velocity $U_\infty \approx 8$ m/s and a very low turbulence intensity of 0.1%. The floor of the test section was covered by two movable smooth steel plates to place the wind-turbine models by means of magnets.

Four reference propeller anemometers (called R2, R3, R4 and R5 in figure 1) were placed after the inlet of the test section to monitor the inlet velocity and mitigate possible drifts of the wind-tunnel motor or variation in the pressure drop throughout the test section due to the farm. These reference anemometers had a higher tower than the farm turbines to reduce the influence of the ground and a low thrust limiting the wake length and intensity behind them.

The turbines used in the experiments had a hub height $H_{\text{hub}} = 60$ mm and diameter $D = 45$ mm. The turbine models used for the wind farm were two-bladed plastic rotors connected to sliding bearing, therefore balancing a negligible overall aerodynamic torque so they were practically freely rotating with a tip-speed ratio $\lambda = \Omega D/2U_\infty \approx 5$, where $\Omega$ indicates the angular velocity. Each turbine model was calibrated with a strain-gauge balance and an
average thrust coefficient $C_T = 8T/(\rho U^2_{\infty} \pi D^2) \approx 0.6 \pm 0.01$ was measured in the velocity range $3 - 10$ m/s. The tower had a magnet at its base to easily place the turbine over the steel plates and change the layout. Three turbines belonging to the first row were monitored, one in the middle and two in the first row edges. Therefore, a total of four propeller anemometers and three observed turbines were monitored during the entire experimental campaign. The velocity of each rotor was measured by means of a dedicated photodiode and a laser light.

For a given staggered layout of the farm, the experimental procedure was to measure initially the velocity of the monitored turbines with the closest farm distance (namely the streamwise spacing, $S_x$), and gradually increase the distance between the first row and the rest of the farm by a distance $S_x + \Delta x$ until $\Delta x \approx 55.6D$, as illustrated in figure 2. The most distant case has been used as the reference case to normalise all the other measurements performed with the same layout. The velocity measured by the three monitored turbines in the first row were first normalised with the average velocity measured by the four reference propeller anemometers located at the inlet of the test section and the Prandtl tube, $U_{\text{ref}}$. In order to limit even more the effect of spurious deviations from the linear calibrations or drifts, the velocity ratio was further normalised with the velocity ratio obtained for the same turbine at a distance of $\Delta x \approx 55.6D$. Therefore, the first normalisation removed effects of wind-tunnel speed variations, while the second normalisation removed effects from eventual drifts in the turbine calibration or systematic effects due to the layout of the first row.

3. Numerical setup

The ORFEUS code, developed in 2016 at KTH, is based on a linearised approximation of the Navier-Stokes equations around an undisturbed incoming boundary-layer profile [9]. The eddy-
viscosity approximation is used to model the Reynolds stresses, where the eddy viscosity is prescribed as a linear function of the height from the ground: the model does not require the boundary-layer approximation and can indeed account for turbulent diffusion in all directions. Wind turbines are introduced in the simulation by means of body forces related to the thrust coefficient. The linearised equations are solved through a spectral approach in a Cartesian grid by means of the Fourier transform in the horizontal plane and Chebyshev polynomials in the vertical non-homogeneous direction, providing a fast and accurate numerical solution of the linearised partial differential equations. Additional details on the equations and the numerical implementation can be found in [10].

The simulation domain was $L_x = 380D$ long and only $L_y = S_y = 2.33D$ wide, while the height of the domain was $L_z = 50D$. These three directions were discretised with $1024 \times 32 \times 60$ points, respectively. It is worth to note that the height of the numerical domain and the height of the ceiling in the experiments were different and this will help assessing the effect of the ceiling interference in the experimentally-measured wind-farm blockage. Periodic conditions were imposed at the side boundaries so that an infinitely-wide farm was simulated with spacing equal to $2.33D$. Due to the use of the Fourier transform in the streamwise direction, periodicity was also imposed at the inlet/outlet (in the perturbation only): to cope for the momentum deficit downstream of the farm, a fringe region was added after the farm to erase its wake and restore the inlet momentum. Due to the accuracy required in the simulation, a very long fringe of $215D$ was present to ensure that the inlet was not affected by small residuals in the momentum deficit from the farm, establishing a small pressure and velocity gradient throughout the domain and affecting the velocity of the first turbine. At the top and bottom of the domain a slip condition was imposed to avoid the emergence of a thin boundary layer.

Only an algebraic turbulence model is present in ORFEUS, where the eddy viscosity is prescribed for every height in the domain, regardless of the presence/absence of turbines. Since the inflow was homogeneous and non-turbulent, the eddy viscosity should be undefined, but here an educated guess for $\nu_T$ was used to introduce turbulent transport throughout the domain and especially above the farm. By assuming that $\nu_T = \kappa u_* z$, where $\kappa = 0.4$ is the von Kármán constant, $u_*$ the friction velocity and $z$ the distance from the ground, an eddy viscosity of $\nu_T = 0.03 U_\infty D$ was assumed, a value encountered in the atmospheric boundary layer at hub height.

The wind turbines were introduced by distributing body forces around the turbine rotor with a Gaussian distribution with length scale (standard deviation) $0.25D$ (thereby avoid oscillation
in the solution), imposing a force associated to the thrust coefficient of the turbine models used in the experiments. Additional simulations of the same farm but with turbines characterised by lower/higher thrust coefficients were performed to assess the sensitivity of the blockage factor to $C_T$ and assess the usefulness of the present measurements performed at a slightly lower $C_T$ than real turbines operating in the field. The hub velocity of the first turbine facing the wind was used as the velocity perceived by the first row. This velocity was then normalised with the hub velocity of an isolated turbine with similar properties to determine the blockage effect.

4. Results

Figure 3 shows the variation of the velocity experienced by the centre turbine located in the first row when changing the streamwise distance, $\Delta x$, between the first row and the farm. The turbine in the middle of the front row experienced the most severe velocity decrease, while one of the turbines of the front row edges experienced a smaller velocity decrease (the other was omitted for clarity sake), which could have been expected by considering that no turbines are present beyond the edges allowing higher flow speeds. It is interesting to note that the presence of the farm downstream has indeed an upstream effect on the velocity of the first row beyond what could have been expected from our understanding of single turbines. Only the first and the last point of the curves in figure 3 are of industrial relevance. It is nevertheless of interest to mention that all those points seem to follow the exponential law

$$U (\Delta x) = U_{ref} - [U_{ref} - U (\Delta x = 0)] \exp \left( \frac{-\Delta x}{5D} \right),$$

sugestting that the first row should become independent of the farm (within a 0.1% effect) after $14D$, namely farther upstream than what currently used. Furthermore, figure 3 indicates that all the turbines in the first row experience a velocity decrease, although that is lower for those located at the edges. One can conclude that no absolute edge speed-ups are present but, on the contrary, edge turbines are less affected by blockage effects and they experience a reduced velocity decrease than the centre turbine, contrary to the general expectation. All the other experiments showed similar trends.

As mentioned before, only the points $U(\Delta x = 0)$ are of interest for industrial applications to estimate blockage losses. By considering all the experiments performed, 85 values of $U(\Delta x = 0)$
were available for the analysis; figure 4 shows a scatterplot demonstrating a clear trend between the points, i.e. suggesting that \( U(\Delta x = 0)/U_{\text{ref}} \) should be related to the number of rows and the area between the turbines. As indicated by the experiments, \( U(\Delta x = 0)/U_{\text{ref}} \) follows an exponential decay with the number of rows, where the coefficients depend on the area \( S_x S_y \). Figure 4 indicates that blockage effects increase as \( N_{\text{rows}} \) increases or \( S_x S_y \) decreases.

Moving now the attention to the simulation results, figure 5 shows a comparison of the velocity at hub height for a turbine belonging to the first row against the normalised velocity detected in the experiments. Both simulation and experiment follow a similar quantitative trend, supporting ORFEUS as a tool to assess accurately and efficiently (each simulation took 10 minutes) blockage problems. The figure reports as well the velocity distribution upstream of the farm (with a shift of \( S_x \) in the streamwise coordinate) following the idea that the first row during the experiments behaved as a propeller anemometer rather than a turbine (as was done in [10]). Since an overestimation of 0.5% is present (between velocity upstream, used as proxy, and velocity measured by the first row with varying \( \Delta x \)), it seems that the upstream velocity effect (which is similar to the problem studied by Bleeg et al. [7]) is stronger than the blockage, although the deviation might be due to an improper normalisation of the velocity trend: this is evident since the velocity decrease follows the same length scale of the experimental data.

Figure 6 shows the sensitivity of the velocity of the turbines located in the first row to the thrust coefficient of the turbines. In the limit case of negligible thrust coefficient, no effect should be present and the first row should experience the free-stream velocity. As the thrust coefficient increases, higher blockage is present until \( C_T \approx 0.6 \) where the variation decreases and the blockage at \( C_T = 0.8 \) seems to be only slightly larger than the one observed for \( C_T = 0.6 \), suggesting that the present experimental results could be representative of a wind farm with realistic thrust coefficient.

5. Conclusions

An experimental and numerical study of upstream effects of wind farms (here referred as blockage effects) has been done in the present work. In the experiments different layouts were investigated
Figure 5. Velocity of the centre turbine according to the experimental results (filled blue circles) and the numerical results (black squares) for various $\Delta x$ for the same setup used in figure 2. (Blue line) exponential law (1). (Black line) velocity decrease upstream of the farm according to the ORFEUS simulation with $\Delta x = 0$.

Figure 6. Velocity of the turbine in the front row for different thrust coefficients of the turbines. The farm layout is the same as in figure 2.

where three observed turbines, belonging to the front row facing the wind, were monitored. Numerical simulations performed with the linearised code ORFEUS mimicked the experiments with the difference that the farm was assumed to be infinitely wide.

The results indicated that the effect of the farm is perceived farther upstream than the 2-4 turbines diameters recommended in the IEC standards [6] and suggested an exponential law for the velocity decrease, with a characteristic length scale independent of the farm configuration. Since the thrust coefficient of the used turbine models ($C_T \approx 0.6$) was less than the one of real turbines ($C_T \approx 0.8$), the blockage effect was expected to be even stronger in real farms, but the numerical results suggested otherwise, i.e. that the blockage obtained from these experiments
is representative of real conditions. Finally, the present database indicates that trends due to blockage exist for the centre turbine and for the turbines on the edges that do not experience any speed-up, contrary to the current expectation.

Acknowledgments

Ms. Claire Peters is acknowledged for the help during the experimental setup. AS is funded by the Swedish Research Council (VR) under a framework grant for strategic energy research and STandUP for Wind.

References

[1] Katić I, Høstrup J and Jensen N O 1986 Proceedings of the European Wind Energy
[2] Ainslie J 1988 J. Wind Eng. Ind. Aerodyn 213–224
[3] Frandsen S, Barthelmie R, Pryor S, Rathmann O, Larsen S, Høstrup J and Thøgersen M 2006 Wind Energy 9 39–53
[4] Walker K, Adams N, Gribben B, Gellatly B, Nygaard N G, Henderson A, Jiménez M M, Schmidt S R, Rodriguez J R, Paredes D, Harrington G, Connell N, Peronne O, Cordoba M, Housley P, Cussons R, Häkansson M, Knauer A and Maguire E 2015 Wind Energy 19 979–996
[5] Koning C 1935 Aerodynamic Theory (Springer) pp 361–430
[6] IEC 61400-12-1 2005 Power performance measurements of electricity producing wind turbines
[7] Bleeg J, Purcell M, Ruisi R and Traiger E 2018 Energies 11
[8] Hagglund P B 2013 An Experimental Study on Global Turbine Array Effects in Large Wind Turbine Clusters Master’s thesis KTH Royal Institute of Technology
[9] Ebenhoch R, Muro B, Dahlberg J Å, Berkestén Hagglund P and Segalini A 2017 Wind Energy 20 859–875
[10] Segalini A 2017 Phil. Trans. R. Soc. A 375 20160099
[11] Ott S, Berg J and Nielsen M 2011 Risø National Laboratory