Numerical Computations of Wind Turbine Wakes

Elforsk rapport: 09:27

Stefan Ivanell

January 2009

Vindforsk Energimyndigheten ELFORSK

Numerical Computations of Wind Turbine Wakes

Elforsk rapport: 09:27

Stefan Ivanell January 2009

Preface

This report is the final report for the the Vindforsk project V-219 ”Numerical calculations of wind turbine wakse. The project has been carried out within tha basic research part of the Vindforsk programme.

The project has been financed by Energimyndigheten as project P 30085-1.

The project has been carried out as a Ph.D. project and in collaboration between Gotland University and KTH (The Royal Institute of Technology) in Stockholm. The project result is presented in a Ph.D. report that will be defended Februari 19, 2009. The thesis ”Numerical computations of wind turbine wakes”, is available at the Royal Institute of Technology web-library.

This report is a summary of the results of the project.

Stockholm januari 2009

Anders Björck

Programme manager Vindforsk II

Sammanfattning

Projektet ”Numeriska beräkningar av vakar bakom vindkraftverk”, kan delas in i tre delar.

I den första delen tog man fram en lämplig numerisk metod för att studera en vak bakom ett vindkraftverk. Ett nära samarbete med DTU (Danmarks tekniska universitet) initierades, vilket ledde till att valet av numerisk kod föll på EllipSys3D som är en kod utvecklad av DTU och Risø. För att representera de enskilda vindturbinbladen utan att lägga för stora beräkningsresurser på fina beräkningsnät kring bladen användes Actuator Line (ACL) metoden. Denna metod utnyttjar tabulerade bladdata så att vare sig geometrin eller gränsskiktet måste lösas upp, vilket innebär att beräkningsresurserna istället kan läggas på vaken. Denna del av projektet resulterade i en lämplig numerisk metod för att simulera vakar bakom vindturbiner och som till följd har lett till en djupare förståelse av grundläggande flödesegenskaper i vakar.

Målet med den andra delen av projektet var att studera grundläggande mekanismer bakom nedbrytningen av vakstrukturen, d.v.s. nedbrytningen av spetsvirvlarna som genereras av turbinbladen. Genom en preliminär stabilitetsstudie där spetsvirveln stördes av en harmonisk störning studerades möjliga moder samt hur dessa påverkade längden på vaken. En viktig kunskap eftersom längden på vaken sätter gränsen för hur nära varandra man kan placera turbiner i stora parker. Resultatet visade på två olika typer av moder varav den ena ledde till snabbare nedbrytning av virvelstrukturen. Studien resulterade även i ett samband mellan turbulensintensitet och vaklängd.

I den tredje och sista delen av projektet simulerades vakinteraktion i en stor park, nämligen Horns Rev, där resultaten även verifierades mot tillgänglig mätdata som erhållits från bl.a. Vattenfall. I det här fallet användes Actuator Disc (ACD) metoden, som är en förenkling av ACL metoden i och med att den använder en disk istället för tre linjer för att representera turbinbladen. Detta är en nödvändig förenklig för att kunna göra simuleringar av 20 vindturbiner, som i detta fall, med dagens tillgängliga datorkraft. Nackdelen med ACD metoden är att man tappar den detaljerade informationen av spetsvirvlarna som erhålls med ACL metoden men den övergripande flödesstrukturen representeras väl. Resultaten visar att metoden fångar produktionsvariationen i parken.

Totalt sett resulterade projektet i en djupare förståelse för flödesstrukturer bakom vindturbiner samt hur flödet ser ut då vakar sammanfaller vid s.k. vakinteraktion. Projektet har dessutom resulterat i möjligheten att m.h.a. numeriska metoder utföra modellering av stora parker samt produktionsvariationer i parken, d.v.s. beroende på var i parken turbinen är placerad. En mycket viktig kunskap då morgondagens stora vindkraftsparker planeras och optimeras.

Summary

Numerical simulations of the Navier-Stokes equations are performed to achieve a better understanding of the behaviour of wakes generated by wind turbines. The simulations are performed by combining the in-house developed computer code EllipSys3D with the actuator line and disc methodologies. In the actuator line and disc methods the blades are represented by a line or a disc on which body forces representing the loading are introduced. The body forces are determined by computing local angles of attack and using tabulated aerofoil coefficients. The advantage of using the actuator disc technique is that it is not necessary to resolve blade boundary layers. Instead the computational resources are devoted to simulating the dynamics of the flow structures.

In the present study both the actuator line and disc methods are used. Between approximately six to fourteen million mesh points are used to resolve the wake structure in a range from a single turbine wake to wake interaction in a farm containing 80 turbines. These 80 turbines are however represented by 20 actuator discs due to periodicity because of numerical limitations.

In step one of this project the objective was to find a numerical method suitable to study both the flow structures in the wake behind a single wind turbine and to simulate complicated interaction between a number of turbines. The study resulted in an increased comprehension of basic flow features in the wake, but more importantly in the use of a numerical method very suitable for the upcoming purpose.

The second objective of the project was to study the basic mechanisms controlling the length of the wake to obtain better understanding of the stability properties of wakes generated by wind turbine rotors. The numerical model was based on large eddy simulations of the Navier-Stokes equations using the actuator line method to generate the wake and the tip vortices. To determine critical frequencies the flow is disturbed by inserting a harmonic perturbation. The results showed that instability is dispersive and that growth occurs only for specific frequencies and mode types. The study also provides evidence of a relationship between the turbulence intensity and the length of the wake. The relationship however needs to be calibrated with measurements.

In the last project objective, full wake interaction in large wind turbine farms was studied and verified to measurements. Large eddy simulations of the Navier-Stokes equations are performed to simulate the Horns Rev off-shore wind farm 15 km outside the Danish west coast. The aim is to achieve a better understanding of the wake interaction inside the farm. The simulations are performed by using the actuator disc methodology. Approximately 13.6 million mesh points are used to resolve the wake structure in the park containing 80 turbines. Since it is not possible to simulate all turbines, the 2 central columns of turbines have been simulated with periodic boundary conditions. This corresponds to an infinitely wide farm with 10 turbines in downstream direction. Simulations were performed within plus/minus 15 degrees of the turbine alignment. The infinitely wide farm approximation is thus reasonable. The results from the CFD simulations are evaluated and the downstream evolution of the velocity field is depicted. Special interest is given to what extent production is dependent on the inflow angle and turbulence

level. The study shows that the applied method captures the main production variation within the wind farm. The result further demonstrates that levels of production correlate well with measurements. However, in some cases the variation of the measurement data is caused by the different measurement conditions during different inflow angles.

Contents

1 Aim of the Project

Knowledge of wind power technology has increased over the years. Lanchester and Betz were the first to predict the maximum power output of an ideal wind turbine. The major break-through was achieved by Glauert who formulated the Blade Element Momentum (BEM) method in 1935.

The design codes of today are still based on the Blade Element Momentum method. It has however been extended to allow for dynamic events, with patch work and ad hoc engineering methods, sometimes of doubtful quality.

Therefore, the aerodynamic research is today shifting toward a more fundamental approach since the basic aerodynamic mechanisms are not fully understood and the importance of accurate design models increases as the turbines are becoming larger.

Recently, complete Navier-Stokes calculations have been performed and today supercomputers offer new possibilities.

The objective of this project is to evaluate existing aerodynamic simulation methods in order to run simulations that provide solutions satisfactory for evaluating the flow field behind one or a number of turbines, i.e., the wake and the wake interaction. From these simulations the basic physical behaviour of the wake will be studied. The project objectives can be divided into three groups.

1.1 Single wake simulation

The first aim is to find a suitable method for simulating the flow field around the turbine, and also to resolve the wake to the extent that it is possible to evaluate the flow field behind the turbine. Particular attention will be given to the circulation close behind the blades.

This section of the project was a part of the larger AEROBIG project which involves five persons: Project Manager Björn Montgomerie, Professor Dan Henningson, Hans Ganander, Ingemar Carlén and Stefan Ivanell. The aim of AEROBIG was to develop design codes that are more accurate than existing codes. Physical features rather than empirical corrections will be utilized to a greater extent.

Hans Ganander and Ingemar Carlén, Teknikgruppen, dealt with the solid mechanical aspects of the project, and Björn Montgomerie, FOI, handled the designing of the aerodynamic engineering methods. The task of this part of the project was to evaluate the circulation in the wake with the best tool available in order to reach a better understanding of the physics close behind the blades.

1.2 Stability analysis

The second aim is to understand the basic mechanisms resulting in the breakdown of the flow structure in the wake. This becomes especially important to understand when looking at interaction between turbine wakes. This knowledge becomes increasingly critical for correct placement of each turbine and spacing between each turbine in the large wind power plants being planned and built today. When building off-shore parks, there is often an area with shallow water where investors want to concentrate as much production as possible. On-shore, there are frequently some limitations on area caused by other factors. To be able to optimize the number of turbines and their positions, knowledge about the length of the wake behind each turbine is necessary. Working knowledge about the basic mechanisms behind breakdown of the distinct tip vortex is therefore important.

1.3 Large park simulation

The final goal is to be able to simulate an entire park. Clear perception about a suitable method and its limitations and basic mechanisms behind the breakdown of the flow structure, etc., are however necessary before setting up an advanced simulation model of a park. When that is achieved and a simulation model for an entire park is created, studies can be made not only on how to optimize one or two turbines but also on clusters of many turbines. This opens possibilities to study how local energy extraction, turbine spacing, yaw angle and park design affects total park efficiency. The results from wake interaction studies will also be important from a fatigue load point of view.

When designing large wind farms there are many parameters to consider in optimizing cost efficiency. Off-shore the foundation cost is strongly related to water depth. The position of the turbines therefore becomes important. It is not unusual that the planner of the park has a limited area with reasonable water depth. (On-shore, similar limitations appear because of houses, urban areas, restricted areas, etc.) Therefore there is an optimization of water depth versus losses in production caused by wake interaction. The overall objective is therefore to use information from single wake simulations and stability analysis to determine how the production varies inside large wind farms. That knowledge will provide important guidelines on the relationship between park losses and distances between turbines inside a wind farm. That relationship will however depend on parameters such as turbulence intensity and geometry of the farm related to the main wind direction.

2 Results and discussion

2.1 Single wake simulation

In the first step of this project, a suitable simulation method was identified for the purpose of wake simulations behind a single wind turbine.

The method, referred to as the actuator line model (ACL) resulted in a 3D-field of the wake. The resolution of that field made it possible to analyse basic flow features of the wake. Emphasis was placed on validating the numerical method.

The flow in the wake was analysed and special interest was given to the circulation in the wake. According to classical theories, the circulation of the tip and root vortices should be conserved and equal the maximum bound circulation at the blades. The result shows that the circulation of the tip and root vortices were of the same size but with different signs, all according to classical theories. The result also illustrates that the circulation of the vortices were of the same order as the bound circulation, also in agreement with the classical theories by Helmholtz.

The first step of the project was thus successful and resulted in a method where 3D-fields of the wake could be simulated. The result also shows correlation with classical theories.

Figure 1 shows the structure of the wake. The figure depicts pressure distribution, velocity distribution and the spiral structure here identified by iso-surfaces of the vorticity. Figure 1 therefore contains significant information. Data are available for the entire 3D-domain. The resolution is of course dependent on the resolution of the computational mesh. This type of field would be impossible to reach with measurements. There are however powerful measurement tools available such as PIV (Particle Image Velocimetry). Still, it would be impossible to map an entire 3D field thus indicating that CFD (Computational Fluid Dynamics) opens up new possibilities. CFD simulations of this size can today be made on super computers during a time period in the order of weeks. It is then possible to study the influence of different parameters by running the simulations repeatedly. The same type of wind tunnel measurements is very expensive compared to the use of supercomputers today. Modern supercomputers are commonly clusters of many standard PC machines combined in a network that allows large tasks to run on a number of processors simultaneously. However the computational code has to be written in a parallel form to allow a task to run on many processors simultaneously.

From the field plotted in figure 1 it is now possible to extract data for different evaluations.

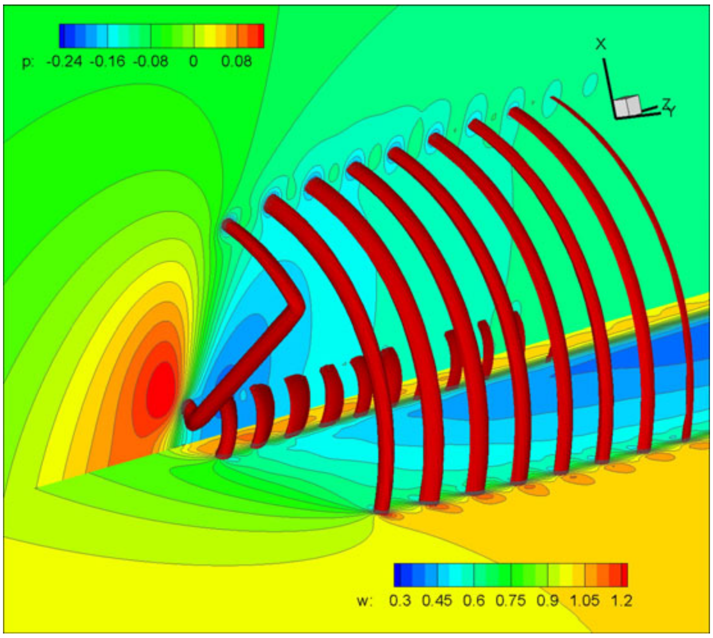


Figure 1, x=0-plane, pressure distribution; y=0-plane, streamwise velocity; iso-surface, constant vorticity.

2.2 Stability investigation

In the second part of the project, the data from the first part were used as a starting point for further investigations of basic flow features. Since the overall aim of the project is to understand how turbines interact in large wind farms, the primary task is to identify and quantify features influencing the wake structure and length. When results of these features are attained one can continue to the next step, relating wind turbine wake length with losses of production in wind farms.

A study of basic mechanisms behind the breakdown of the spiral system was initialized. The mesh was the same as in the first step of the project. The steady state simulations of that part were now used as initial conditions for time dependent simulations. At the starting point of unsteady simulations, a harmonic perturbation was introduced close behind the blade tip. The perturbation was introduced by including a body force. By changing the amplitude and frequency of that perturbation the response from the spiral system could be evaluated. The result shows that the growth rate of the introduced perturbation was dispersive, i.e., different frequency regimes resulted in different type of modes. When changing the amplitude for a specific frequency it was possible to conclude that the growth rate was not related to the perturbation amplitude, meaning that a linear growth rate could be extracted. A larger amplitude leads however to an earlier breakdown of the spiral structure since it has a larger amplitude at the starting point. This also makes it possible to relate the introduced perturbation to turbulence intensity. This analysis thus results in a relationship between the ambient turbulence and wake length. It is difficult to quantify the turbulence intensity level to a specific perturbation level, but the general physical behaviour can be explained. The result shows that the relationship between the turbulence intensity, i.e., perturbation amplitude in this case, and wake length is semilogarithmic, see figure 2. From figure 2 one can conclude that the wake length depends on the perturbation frequency which then can be related to the frequency in the ambient turbulence. The study of the influence of the perturbation frequency resulted in an identification of two types of modes. In the first mode the entire spiral system is oscillating in phase. That is, all spirals are extending from the free stream velocity in the same direction at some azimuthal position. This can occur in all three directions (axial, radial and azimuthal). The result did however show that the main extension was in axial and radial directions.

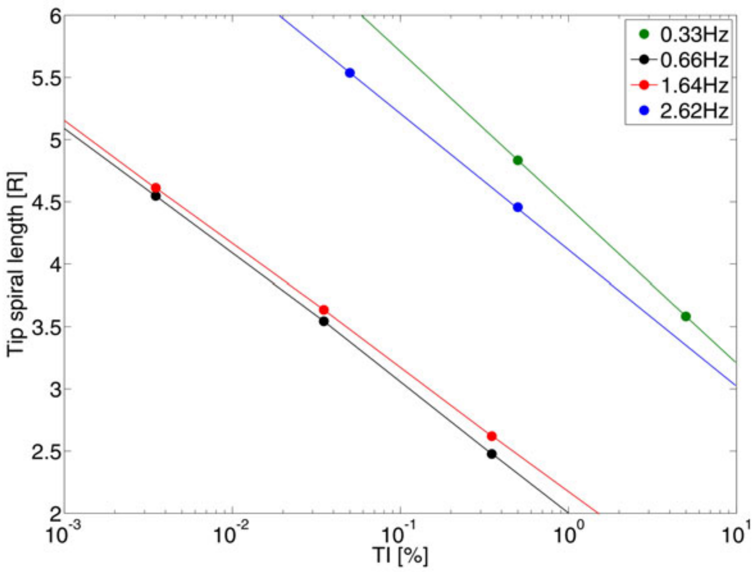


Figure 2, The figure shows the wake length related to turbulence intensity and frequency.

The second mode consists of out of phase motions of the spirals. This mode corresponds to the case when every second spiral extends from the free stream velocity in opposite directions at some azimuthal position. That is, every second spiral extends in positive axial or radial directions while the other spiral moves in the opposite direction at some point. When identifying different modes, the interaction of the two spiral arcs located closest together is of most interest. The complex spiral system consists of three spirals within each other but the interaction is done in pairs. Therefore, when analysing the interaction the local interaction between the spiral arcs and its closest spiral arc is identified regardless from which of the three spirals it originates.

The results show that the mode with every second spiral out of phase results in the largest growth rate. In both cases the growth results in pairing of the vortices due to non-linear effects. The mode with every other spiral out of phase, results in an earlier breakdown of the spiral system. That mode occurs at around 0.66 and 1.64 Hz as can be identified in figure 2.

Figure 3 identifies the spiral system by an iso-surface of the vorticity. The colour coding at that surface corresponds to the axial position. The mode with every other spiral out of phase described above can clearly be identified in the figure. It is possible to see how the instability grows from about z=17.5 which corresponds to about 4 radii behind the turbine. The unit of z is [R], i.e., the radius of the turbine. In this case the varicose mode has a wavelength that corresponds to 4.5 wavelengths for one revolution.

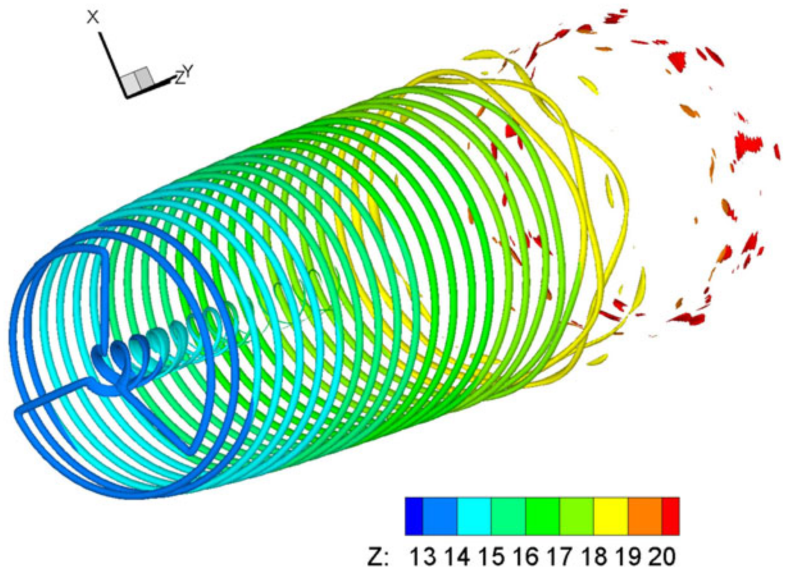


Figure 3, An iso-surface of the vorticity.

The second step of the project enhances our understanding of the basic breakdown of the wake structure and provides important data about the effect of different spacing between turbines. Collectively, this represents valuable information for moving to the third step of the project.

2.3 Farm simulation

In the last step of the project an entire wind farm with 80 turbines has been simulated. In this case the actuator disc method is used instead of the actuator line method. The limitation of using the actuator disc method is that individual tip vortices are not captured. The size of the simulation does however require simplification in order to handle the number of turbines. By using the actuator disc method there is still need for additional simplification since a computation with 80 turbines would be impossible to handle. Therefore, the two most central rows of turbines are simulated with periodic boundary conditions on both boundaries toward the other rows of turbines, thus assuming an infinitely wide farm. The farm simulated is the Horn Rev wind farm located 15 km off the west coast of Denmark. The farm contains 8 times 10 turbines positioned according to figure 4. In this simulation columns 4 and 5 are projected with periodic conditions assuming an infinitely wide wind farm. This offers a good approximation when the inflow angle is small compared to the direction of the rows. When the wind direction becomes critical, contribution from "non existing" wind turbines outside the farm will be present. In this study we concentrate on wind directions in the regime of plus/minus 15 degrees. The error from this approximation will therefore be small since the non-existing turbines outside the farm are located approximately 18 degrees from the north boundary and 35 degrees from the south boundary to the turbines in the two centre lines that will be affected first, see figure 4.

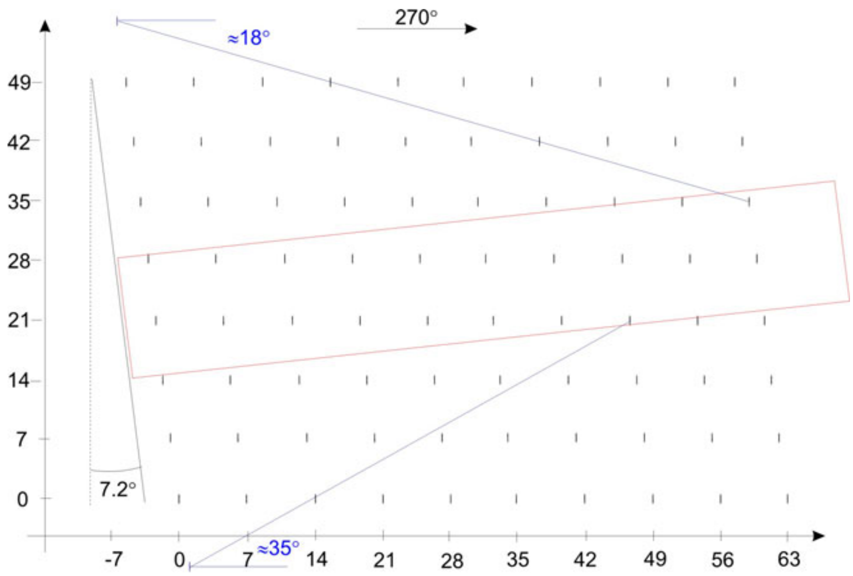
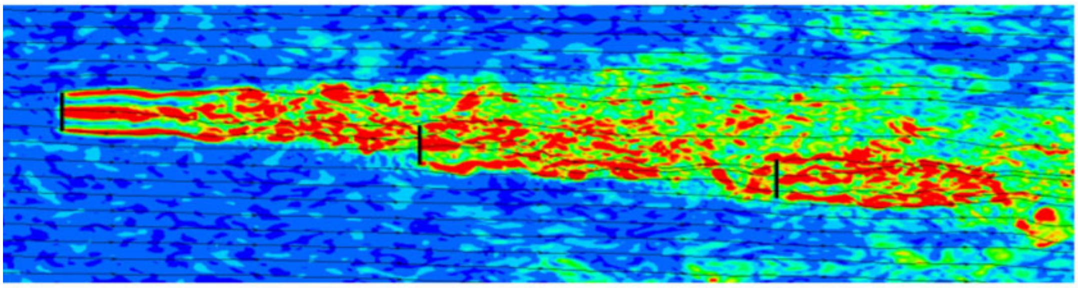
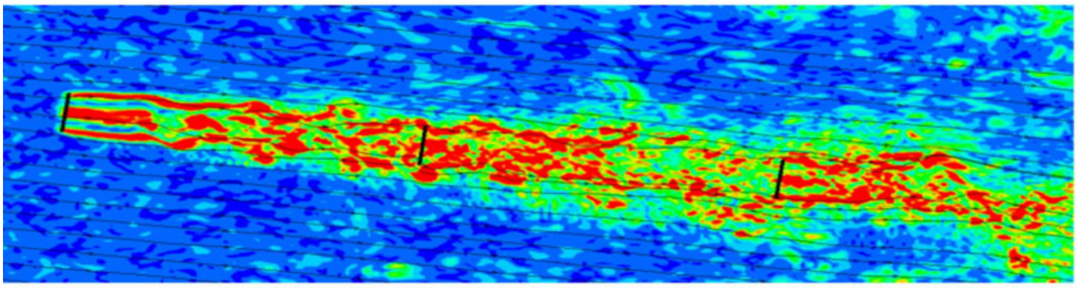


Figure 4, Layout of Horns Rev Wind Farm

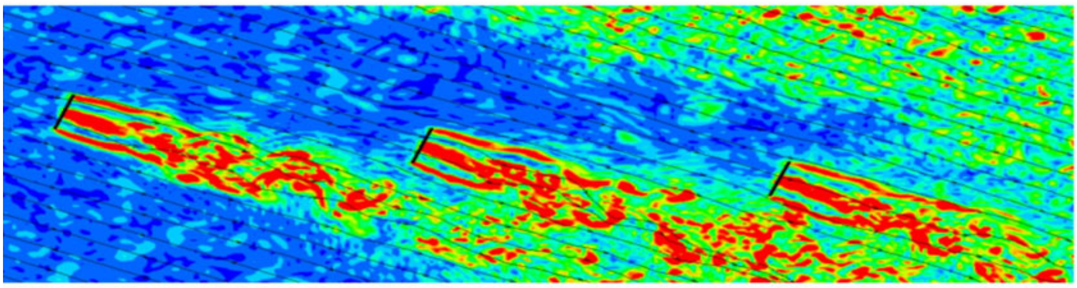
Figure 5 shows the flow at hub height for the three first turbines in column 5 at three different inflow angles, i.e., 265°, 270° and 285°. From the observed wake interaction it is obvious that the downstream turbines experience different flows in the three different cases depicted here.



(a)



(b)



(c)

Figure 5, Vorticity at hub height. The figures illustrate different flow directions. The flow direction is identified by a number of stream-lines. (a) 265°, (b) 270°, (c) 285°.

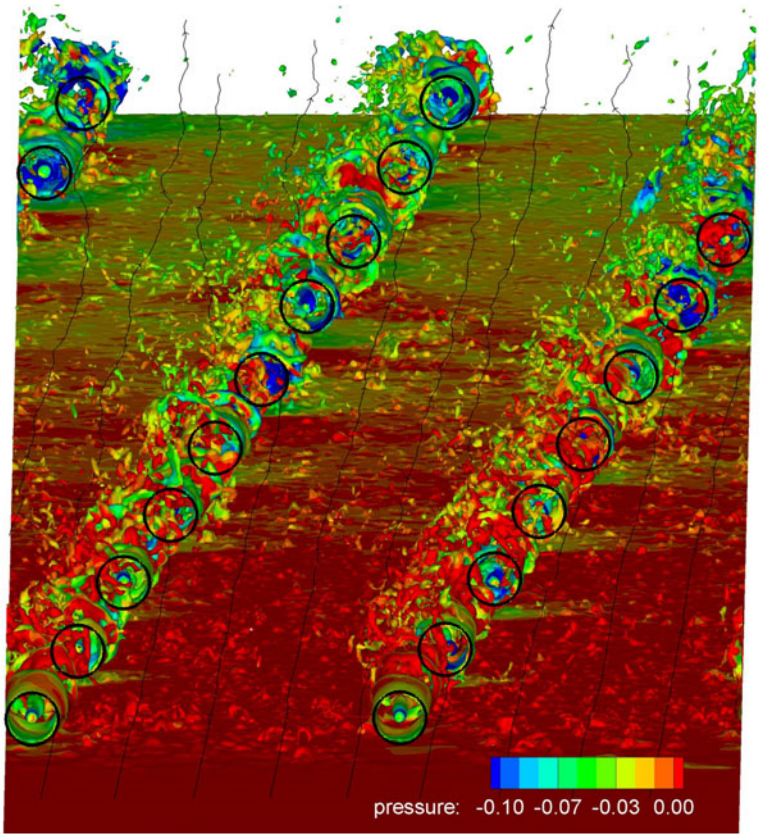


Figure 6, 3D field of the computational domain. The figure illustrates an iso-surface of the vorticity. At the iso-surface, a contour of the pressure is depicted. The turbines are here inferred by a circle.

Figure 6 shows a 3D field of all simulated turbines. The wakes are illustrated by an iso-surface of the vorticity. Note, that what appears to be the ground surface, is the same iso-surface as that which appears locally around each turbine and it is located at a height above the ground surface. The colour coding depicted at the iso-surface represents the pressure, the levels can be identified by the legend.

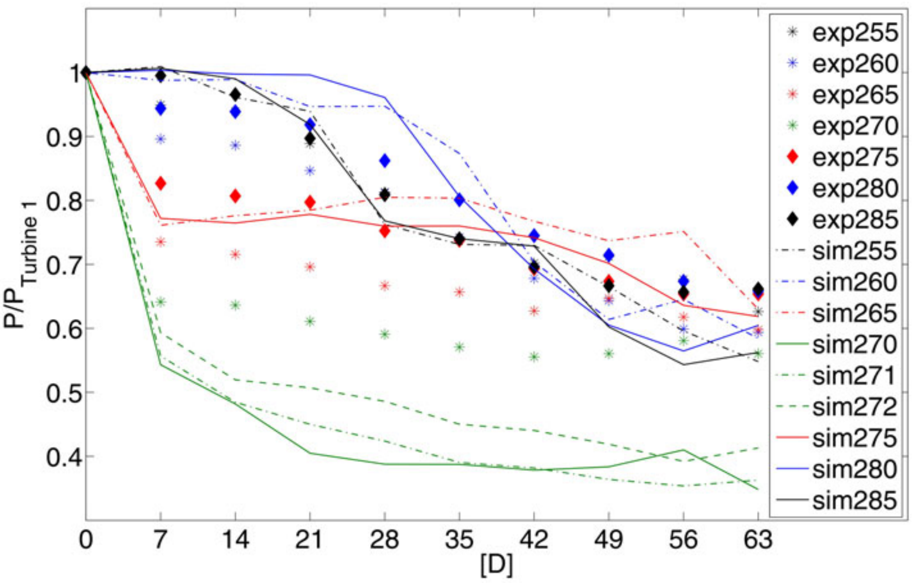


Figure 7, Simulation results compared with measurements. Results from both simulations and measurements are shown for inflow angles between 255 and 285 degrees, i.e., +/- 15 degrees from the westerly direction.

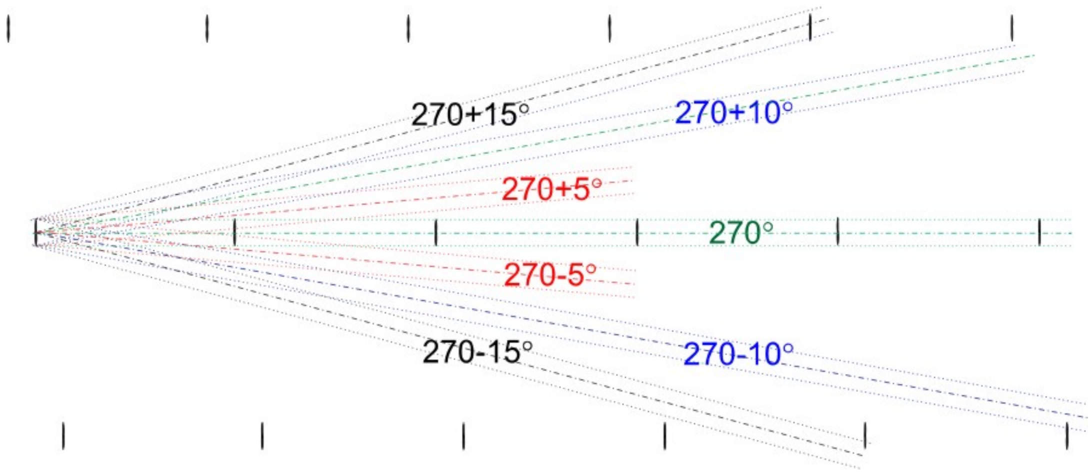


Figure 8, Wake interaction due to different wind directions.

Figure 7 illustrates both measured and simulated results. The measured data are based on measurements in sectors of plus/minus 2.5 degrees from the simulated wind direction. The simulated results are plotted in the corresponding colour as the measured data. The simulated cases with an inflow angle of -(5, 10 and 15) degrees are here plotted with a dotted line. Corresponding measured data are plotted with a star. The simulated cases with an inflow angle of +(5, 10 and 15) degrees are plotted with a solid line.

Corresponding measured data are plotted with a diamond. The case corresponding to full wake interaction, i.e., 270 degrees or 0 inflow angle to the column alignment, is here depicted with a solid green curve. The dot-dashed and dashed curves correspond to inflow angles of +1 and +2 degrees. These cases have been studied in order to identify the sensitivity of small deviations from the full wake case. All values have here been normalized with the production of the first turbine in wind direction.

Figure 8 illustrates the wake interaction in the different cases. Considering the case with an inflow angle of 285 degrees it is possible to identify how the wake interaction starts to be clearly noticeable at the fourth row of turbines, see figure 7. When comparing with figure 8, this corresponds to the position where the wake of the first turbine is getting close to a downstream turbine. Further downstream, the production clearly drops to the next row, i.e., the fifth row, see figure 7. When comparing with figure 8, this corresponds to the point where full wake interaction occurs. Further downstream the production averages out for about three turbines, after which the production again drops, see figure 7. The lowest production occurs at the ninth row, which corresponds to where the full wake interaction takes place for the second time.

When conducting the same analysis for the case with 280 degree inflow angle, one can note similar behaviour. But now the essential drop of production occurs further downstream. When comparing with figure 8, it is observed that the wake from the first turbine passes the fifth turbine at a greater distance than the wake from the first turbine in the 285 degree case was to the fourth turbine. Therefore, the production drop for the fifth turbine is less than the drop for the fourth turbine in the 285 degree case. It is also obvious that the production for the sixth turbine in the 280 degree case is higher than the production of the fifth turbine in the 285 degree case. This is because the 280 degree case does not have a full wake interaction, compare with figure 8. When comparing these two cases with measurements the simulations underestimate the wake interaction until full wake interaction occurs and overestimate the wake interaction after the point of the first full wake interaction. However, it is important to remember that measurement data are based on a sector of +/- 2.5 degrees while the simulations are performed at one exact direction.

When considering the cases with an inflow angle of +/- 5 degrees, i.e., the 265 and 275 degree cases, it is possible to note that both results are between the measured data at rows one to four. When looking at figure 8 it is also evident that an inflow angle of +/- 5 degrees could not affect the measured data to the extent plotted in figure 7 where the production of the second row deviates about 10% compared to the production of the first turbine. Therefore one must conclude that the circumstances of the measuring period for the cases with +/- 5 degree inflow angle are very different. The simulated results are however in the same order as the measured data which should verify that the levels of the simulated production are well predicted. Further downstream the case with -5 degree inflow angle results in slightly higher values compared to the case with an inflow angle of +5 degrees. That could be explained by the geometry of the farm. The cases with north inflow angles experience a longer distance to the next turbine of the south column compared to a case where the wind is coming from the south, and the distance to the next turbine in the north column is shorter. Full wake interaction would occur at about the eleventh row in the -5 degree case, however this case has only 10 rows so the effect will be small. The last drop in the -5 degree case, i.e., between the ninth and tenth rows, may however be influenced by the wake from the first turbine.

When considering the full wake case, the 270 degree case, it is clear that the simulation overestimates the wake interaction. However, when considering that the measured data are based on a sector of +/- 2.5 degrees and also comparing with a simulation using inflow angles of +1 and +2 degrees, the overestimation does not appear to be as large as first predicted.

3 Conclusions

In step one of this project the objective was to find a suitable numerical method suitable to study both the flow structures in the wake behind a single wind turbine and to simulate complicated interaction between a number of turbines. In this first step approximately five million mesh points were used to resolve the wake structure in a 120 degree domain behind the turbine. The study resulted in increased comprehension of basic flow features in the wake, but more importantly it resulted in the use of a numerical method very suitable for the upcoming purpose.

The introduced simulation method was performed by combining the in-house developed computer code EllipSys3D with the actuator line and disc methodologies. In the actuator line and disc methods the blades are represented by a line or a disc on which body forces representing the loading are introduced. The body forces are determined by computing local angles of attack and using tabulated aerofoil coefficients. The advantage of using the actuator line or disc techniques is that it is not necessary to resolve blade boundary layers. Instead, the computational resources are devoted to simulating the dynamics of the flow structures.

The second objective of the project was to study the basic mechanisms controlling the length of the wake to obtain better understanding of the stability properties of wakes generated by wind turbine rotors. To determine the stability properties of wind turbine wakes a numerical study on the stability of the tip vortices behind the Tjaereborg wind turbine was carried out. The numerical model is based on large eddy simulations of the Navier-Stokes equations using the actuator line method to generate the wake including tip vortices. To determine critical frequencies the flow is disturbed by inserting a harmonic perturbation. The results showed that instability is dispersive and that growth occurs only for specific frequencies mode types. The study also provides evidence of a relationship between the turbulence intensity and the length of the wake. The relationship however needs to be calibrated with measurements.

In the last project objective, full wake interaction in large wind turbine farms were studied and verified to measurements. Large eddy simulations of the Navier-Stokes equations are performed to simulate the Horns Rev off shore wind farm 15 km outside the Danish west coast. The aim is to achieve a better understanding of the wake interaction inside the farm. The simulations are performed by combining the in-house developed computer code EllipSys3D with the actuator disc methodology. Approximately 13.6 million mesh points are used to resolve the wake structure in the park containing 80 turbines. Since it is not possible to simulate all turbines, the 2 central columns of turbines have been simulated with periodic boundary conditions. This corresponds to an infinitely wide farm with 10 turbines in downstream direction. Simulations were performed within plus/minus 15 degrees of the turbine alignment. The infinitely wide farm approximation is thus reasonable.

The results from the CFD simulations are evaluated and the downstream evolution of the velocity field is depicted. Special interest is given to what extent the production is dependent on the inflow angle and turbulence level.

The study shows that the applied method captures the main production variation within the wind farm. The result further demonstrates that levels of production correlate well with measurements. However, in some cases the variation of the measurement data is caused by the different measurement conditions during different inflow angles.

Overall, the project resulted in increased knowledge about the flow structures behind wind turbines and the interaction of a number of turbines. The project also established numerical methods utilizing possibilities to simulate production variation inside large wind farms, a necessary requirement in order to optimize the large wind turbine farms of the future. A third result of the study demonstrated a relationship between turbulence intensity and wake length, making it possible to optimize the spacing between turbines in wind farms. Collectively, the project established new simulation possibilities for the next generation of wind farm development. However, since these simulation methods are dependent on large computers and still demand extensive simulations, future work should concentrate on implementing these methods using an engineering approach to industrial codes. This does, however, require further development and especially computer resources to simulate more cases than have been possible within this project, i.e., to run simulations of a number of velocities and turbulence intensities corresponding to more complex terrain, and verifying these simulations with measurements. Engineering methods could then be based on a database with data from a wider regime of cases. Additional understanding of what occurs during interaction between a number of turbines can be achieved by running wake interaction studies using the actuator line method, instead of actuator disc methods, utilizing the computational possibilities of tomorrow. Such simulations, in conjunction with detailed wind tunnel measurements, could provide knowledge on how to control the breakdown of the wake behind the turbines and give further possibilities to optimize the placement of wind turbines in a park.