Optimization of Large Wind Farms, The Nordic Consortium, Activity report 2009-2012

Elforsk rapport 13:12

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Preface

In order to increase the knowledge on how to optimize today's and tomorrow's large wind farms, research is carried out in a Nordic Consortium with researchers in Sweden, Denmark and Norway. The research spans over details in the wake to methods for wind farm optimization and wake affects of entire wind farms. Much collaboration is also carried within the two IEA WIND tasks Wakebench and Mexnext.

The work within the Nordic Consortium is financed by Swedish Energy Agency, the research program VindForsk III, the Nordic Energy Research Top Level Research Initiative Danish Research Council and Industrial partners in Sweden and Norway.

Of the subtasks in the Nordic Consortium, subtask 3, 6, 7 and partly 8 has been financed through Vindforsk III as projects V-333, V-355 and V-370.

This report is the activity report for the period 2009-2012 for the Nordic Consortium, and also the final report for Vindforsk III in the projects V-333, V-355 and V-370.

Dan Henningson from KTH and Stefan Ivanell at the University of Gotland and KTH has been the project leaders of the Vindforsk Projects.

Vindforsk – III is funded by ABB, Arise windpower, AQSystem, E.ON Elnät, E.ON Vind Sverige, Energi Norge, Falkenberg Energi, Fortum, Fred. Olsen Renwables, Gothia wind, Göteborg Energi, HS Kraft, Jämtkraft, Karlstads Energi, Luleå Energi, Mälarenergi, o2 Vindkompaniet, Rabbalshede Kraft, Skellefteå Kraft, Statkraft, Stena Renewable, Svenska Kraftnät, Tekniska Verken i Linköping, Triventus, Wallenstam, Varberg Energi, Vattenfall Vindkraft, Vestas Northern Europe, Öresundskraft and the Swedish Energy Agency.

Comments on the work have been given by a reference group with the following members:

Jens Madsen, Vattenfall Vindkraft

Andreas Gustafsson, Energimyndigheten,

Ulf Tollaksen, Triventus

Francesco Sottini, E.ON Vind Sverige

Stockholm March 2013

Anders Björck

Programme manager Vindforsk-III

Electricity- and heat production, Elforsk

Optimization of Large Wind Farms

Activity report 2009-2012, The Nordic Consortium

Stefan Ivanell, I. Carlén, K. Nilsson, S. Sarmast, Y. Odemark, S. J. Andersen, G. Teneler, O. Eriksson, S. P. Breton, E. Åkervik, A. R Gravdahl, J. Fransson, R. Mikkelsen, J. N. Sørensen & Dan Henningson

Sammanfattning

Det Nordiska konsortiet är ett samarbete mellan de tre universiteten KTH, Högskolan på Gotland och Danmarks Tekniska Universitet, DTU, tillsammans med flertalet företag från de nordiska länderna, exempelvis Teknikgruppen och Vattenfall Vindkraft.

Konsortiets mål är att utveckla och förbättra metoder för hur stora vindkraftsparker kan styras, både för att få en högre produktion men även så att förslitningslaster minskas och underhållskostnader minimeras samt livslängden på turbinerna förlängs.

För att kunna utveckla denna typ av styr- och kontrollsystem krävs en förbättrad grundläggande förståelse om hur vindkraftverk påverkar varandra, det vill säga hur vakar interagerar med varandra där vaken är det uppbromsade området bakom ett vindkraftverk sett i vindriktningen.

Inom det nordiska konsortiet bedrivs många olika delprojekt och inkluderar 6 doktorander i Sverige och Danmark.

För att få en grundläggande förståelse av vindvakens karakteristik genomförs numeriska strömningsberäkningar (CFD) samt vindtunnelmätningar där påverkan från olika viktiga parametrar studeras. Syftet är att kunna avgöra hur vindkraftverk kan placeras optimalt beroende på hur de platsspecifika förhållandena ser ut.

Två av delprojekten studerar vakflödet efter ett isolerat vindkraftverk. Syftet med dessa studier är att öka den grundläggande förståelsen för hur den individuella vindvaken propagerar och interagerar med sin omgivning. En hörnsten i dessa projekt är att studera vakens stabilitet samt mekanismerna bakom vakens nerbrytning. Den ökade förståelsen för den individuella vaken används sedan i de tre av de andra delprojekten där flera turbiner sätts samman i rader och parker som simuleras med CFD och där hela flödesfältet tas fram och kan utvärderas. Utifrån flödesfältet kan verkens produktion analyseras och sättas i samband med viktiga aspekter såsom ambient turbulensnivå, effektstyrning samt avstånd mellan enskilda vindkraftverk.

Ett av delprojekten studerar även vakar från stora vindkraftsparker samt hur de påverkar flödet långt, i storlekordningen flera kilometer, nerströms vindkraftparken. I dagsläget planeras många stora vindkraftsparker till havs. Vindkraftsparkerna kommer därför sannolikt påverka varandra genom att stjäla vind från varandra. Resultatet vid ett sådant scenario blir att den totala produktionen för de olika parkena minskar. Projektet syftar till att genom CFD beräkningar analysera denna påverkan. Då dessa beräkningar täcker in mycket stora områden så krävs en ansenlig datorkapacitet. Dessa simuleringar ligger därför i framkanten på vad som är möjligt med dagens tillgängliga beräkningskapacitet.

Oavsett om man genom CFD studerar individuella eller multipla vakar så kräver den här typen av simuleringar en mycket stor datorkapacitet. Beräkningarna fortgår i regel under ett flertal dagar på hundratals processorer. Då många simuleringar krävs för att få en bild av flödet från tar dessa mycket tid i anspråk. Dock ökar tillgändlig datorkapacitet kontinuerligt och vad som beräknas idag var omöjligt att utföra för några år sedan.

Inom industrin används förenklade modeller som är avsevärt effektivare än de som används inom forskningen då kraven på snabba resultat är högre. Dock har dessa förenklade modeller begränsningar och behöver verifieras med mer avancerade beräkningar som görs på universiteten. Då datorkapaciteten ökar kan dock mer och mer avancerade metoder användas även av industrin.

I dagsläget styrs vanligen varje vindkraftverk individuellt, men ett delmål med det nordiska konsortiet är att ta fram en parkstyrningsmodell som styr hela parken för att få ut så mycket energi som möjligt och minimera laster. Detta kan till exempel göras genom att ta ut mindre energi i början av parken, det vill säga de vindkraftverk som träffas först av vinden. Det skulle kunna innebära att mer energi tas ut totalt sätt ur parken men framför allt att förslitningsskador minskas för särskilt utsatta verk. Under arbetets gång har olika robusta principer för parkstyrning identifierats, och enkla algoritmer har utvecklats och demonstrerats.

De mjukvaror som idag används för dynamiska simuleringar av vindkraftverk under designfasen, körs i princip i realtid på enkla kontorsdatorer och tidsåtgången kan räknas i minuter. För att man med ska kunna utföra optimering av hela vindkraftsparker med i storleksordningen 50-100 vindkraftverk, behövs analysverktyg som är snabba och flexibla. Inom projektet har därför metoder utvecklats för effektiv simulering av de storskaliga turbulenta rörelser som transporterar enskilda vakar i parken. Utgångspunkten är här inte grundläggande strömningsekvationer som för CFD, utan istället statistiska beskrivningar av vinden som är väl etablerade inom meteorologin. Resultatet av utvecklingen har blivit avsevärt kortare simuleringstider och betydande minskning av behovet att mellanlagra resultat. Det är viktigt att påpeka att all reglering här utgår från en detaljerad kunskap om rotorns aerodynamiska egenskaper. I takt med att rotorbladen blir längre och mer flexibla måste man överge etablerade aerodynamiska koncept där man utgår från vindkraftverkens löptal. Detta medför att stora mängder av aerodynamiska tabeller måste genereras med icke-linjära flexibla rotor-modeller. Detta har i projektet lösts genom vidareutveckling av pre-processorer till befintliga aeroelastiska beräkningsverktyg.

Resultaten från projektet kan sammanfattas i följande punkter:

- Ökad förståelse av vakdynamik och hur vaken bryts ned. Det som kunde observeras i vindtunnlar för 10 år sedan kan nu beräknas och vi har en bättre förståelse för de grundläggande fenomenen.
- Verifierade flödesmodeller genom deltagande i IEA (International Energy Agency) Annex 29, det s.k. MEXICO projektet. I detta projekt utfördes vindtunneltester på en turbin med en diameter på 4,5 meter i Europas största vindtunnel.
- Använd modell har validerats med tillgänglig produktionsdata från den befintiliga vindkraftsparken Lillgrund. Resultatet visar att modellen är mycket kapabel att estimera produktionstrender samt produktionsnivåer i parken.
- En kontrollrutin för styrning av vindkraftverk i parker har implementerats i EllipSys3D.
- Ett första steg mot en optimering av vindkraftsparker har tagits genom utveckling av ovan nämnda kontrollrutin, verifiering av flödesmodeller samt initiala tester av varierat lokalt energiuttag i parker. De initiala testerna visar att genom att enbart ta ut mindre energi i första raden (i vindriktningen) så erhålls varken mer eller mindre total energi. Den är i stort sett oförändrad. Dock innebär minskat energiuttag i första raden att vaken som träffar nästkommande vindkraftverk är mindre skadlig och det är därför i utmattningsperpektiv en god idé att styra individuella vindkraftverk även om det inte innebär mer energiuttag.
- Projektet har lagt grunden för att i nästa steg även implementera lastberäkningar för individuella vindkraftverk. Då kan parken optimeras utifrån både produktions- och utmattningsperspektiv med högre produktion och minskade underhållskonstnader samt ökad livslängd.

Abstract

The overall aim of the Nordic Consortium is to increase the knowledge on how to optimize today's and tomorrow's large wind farms, i.e., how to increase production and minimize loads. The result will therefore ensure lower cost per produced energy.

The project is divided into eight subtasks. They are all working towards the same goal, i.e., aiming for an increased total understanding of flows inside and around wind farms. Some subtasks are focusing on fundamental understanding, some are more applied while some are on the edge to implementation that can be used by the industry in the near future. The project is also active in a number of international projects related to a number of these subtasks.

This report summarizes all activities from 2009-2012 within the Nordic Consortium. However, not all activities are financed by the research project VindForsk III.

The project has resulted in an increased understanding of wake dynamics and tip spiral break down. The fundamental study of the spiral system and wake dynamics has resulted in a much greater understanding of the wake physics, based on both experimental and numerical work. Today we do understand the principal key questions to how and why the spiral system breaks down. A model that links the turbulence level and wake length has been developed. There are however many questions remaining on how different parameters affect the model to be able to use this model on a daily basis for design of wind farms.

The results show that given specific parameters such as wind speed, turbulence level, boundary layer profiles etc. the power variation inside large wind farm is estimated with a high accuracy. The model, i.e., the EllipSys3D code, could therefore be used for farm layout optimization and estimation of power production, fatigue loads etc. The high accuracy of the model is a result from joint research activities in different subtasks since the fundamental understanding from some tasks is needed for the more applied studies in other tasks. A new controller, among other things, has been developed which is needed for a realistic power estimation but that controller is also the first step in the farm optimization.

The first step in optimization is taken by downrating of individual turbines. The result shows that downrating only the first row of turbines does not result in a higher farm production. However, it is expected that the fatigue load will be decreased. The project is in a phase where CFD and structural loads can be combined for a full optimization of the farm control system.

The project has also resulted in the verification of a fast vortex line model that could be used together with models developed in the project for optimization.

A close collaboration has been established with the Swedish industry, for example with Vattenfall and Scandinavian Wind. The project resulted in a first step towards a farm optimization. The next step ahead is to take this to the next level implementing a full farm controller.

The icing studies are in their initial stage but have reviewed what has been done in this area until today. Initial studies have shown that the proposed methods are suitable for further studies.

The farm-farm studies are also in their initial stage. A review of what has been done in this area until today has been performed and initial studies have shown that the suggested methods and test simulations are suitable for further studies.

The computational capacity increases every day and that opens new possibilities. Today, there are however still many questions remaining and even though the computational capacity increases we still need to make simplifications and approximations to be able to study the very complex situations that we do have when it comes to wind turbines operating in clusters in atmospheric boundary layers. It is important to also mention that this increase in computational capacity allows to take new steps towards a more complete understanding of the complex physics.

To summarize, the main conclusions are:

- Increased fundamental understanding of the wake physics and the mechanisms behind wake

breakdown. What could be observed in wind tunnels 10 years back can now be understood and simulated with high accuracy.

- Flow models have been verified through participation in IEA (International Energy Agency) Annex 29, i.e., the MEXICO project. In this project wind tunnel experiments were performed in the largest wind tunnel in Europe using a wind turbine with a diameter of 4.5 meter.
- Used numerical models have been validated with available measurements from the Lillgrund wind farm. The result shows agreement with a very high accuracy and demonstrates that the model is capable of accurate estimations of the production variation inside large wind farms.
- A generator torque controller that makes it possible for individual turbines to adapt to the conditions in which thay find themselves inside large wind farms have been implemented in the EllipSys3D code.
- A first step towards optimization of wind farms has been made through the above mentioned control software combined with initial simulations of downrating of individual turbines. The initial results show that by only derating the first row of turbines, one cannot extract more total energy from the wind farm. However, by derating the first row of turbines, the second row will experience weaker wakes and thereby the fatigue loading will decrease.
- The project set a foundation for next step, i.e., to also evaluate loads of individual turbines. Then, the farm can be optimized on both production and load perspectives and reach higher production, lower fatigue loading and thereby decrease the maintenance cost and increase the lifetime of the turbines.

Contents

Chapter 1

Introduction

1.1 Aim of the Nordic Consortium Project

Wind turbines clustered in wind farms are generally subject to a mixed type flow which in part is undisturbed and in part influenced by the wake from upstream turbines. Considering a single wind turbine, the wake generated by a wind turbine rotor consists of a vortex sheet which is formed by the lift force distribution along the blades. The vortex sheet forms a strong root vortex and distinct tip vortices. The tip/root vortex system is unstable, and due to self-induced instability mechanisms and ambient atmospheric turbulence, it eventually breaks down and forms small-scale turbulence further downstream. The helical tip vortices are the most interesting and potentially the most dangerous feature of the wind turbine wake. They contain significant angular momentum which poses a risk for the other turbine that is affected by the upstream wind turbine wakes. If the wind turbines are clustered close to each other, these coherent structure may interact with other turbines. Such interactions increase the dynamic loading of the downstream turbines and reduce performance. In addition, the detailed knowledge of the unsteady wake development helps to understand problems related to vibrations, noise and structural load. These issues are studied by the international research group within the Nordic Consortium with the common goal to reduce costs through optimizing wind farms.

Therefore, the overall aim of the Nordic Consortium is to increase the knowledge on how to optimize todays and tomorrows large wind farms, i.e., how to increase production and minimize loads. By minimizing loads, one ensures reduced maintenance costs and increased life time. The result will therefore ensure lower cost per produced energy unit.

1.2 Background

The Nordic Consortium was initialized by Dan Henningson and Stefan Ivanell as a continuation of Stefans PhD project. In Stefans PhD project a close collaboration was developed with The Technical University of Denmark (DTU) and the group lead by Jens Sørensen. Initial contacts were also developed with Norwegian partners. In 2009, a good basis was therefore in place for a larger collaboration within a Nordic Consortium. A close collaboration had also been established with the Swedish industry ensuring that existing experience is used and that developed knowledge could be transferred. The main partners are Vattenfall with an experince of large wind farms and Teknikgruppen with experience in the area.

Financing was received by the Swedish Energy Agency, the research program VindForsk III, the Top Lever Research Initiative (TRI), Danish Research Council and Industrial partners in Sweden and

Norway. The VindFosk III part of the project ends with this report, i.e., end of 2012. The Energy Agency part is financed until mid 2013. The part financed from TRI ends in 2014. A reference group was assigned to the project containing representatives from the Swedish Energy Agency and the Industry within the Nordic countries, see table 1.2. The project started in late fall 2009. Table 1.1 show current project participants.

Table 1.1: Nordic Consortium Participants

Name	**Title**	**Project role**	**Affiliation**
Swedish Participants			
Dan Henningson	Professor	Project manager	KTH
Görkem Teneler	M.Sc.	PhD Student	KTH
Ingemar Carlén	M.Sc.		Teknikgruppen
Jan-Åke Dahlberg	M.Sc.		Vattenfall WP AB
Jens Fransson	Assoc. Professor		KTH
Karl Nilsson	M.Sc.	PhD Student	KTH/HGO
Ola Eriksson	M.Sc.	PhD Student	KTH/HGO
Sasan Sarmast	M.Sc.	PhD Student	KTH
Simon-Philippe Breton	Researcher		HGO
Stefan Ivanell	Assoc. Professor	Ass. Proj. manager	KTH/HGO
Ylva Odemark	M.Sc.	PhD Student	KTH
Danish Participants			
Jens Nørkær Sørensen	Professor		DTU/HGO
Kurs S. Hansen	Assoc. Professor		DTU
Robert Mikkelsen	Assoc. Professor		DTU
Søren juhl Andersen	M.Sc.	PhD Student	DTU
Norwegian Participants			
Arne R. Gravdahl	PhD		WindSim AS
Espen kervik	PhD		Kjeller Vindtekknik
Erik Berge	PhD		Kjeller Vindtekknik
Sónia Liléo	PhD		Kjeller Vindtekknik

Table 1.2: Reference Group

Name	**Affiliation**
Andreas Gustafsson	Swedish Energy Agency
Francesco Sottini	EON Wind
Jens Madsen	Vattenfall Windpower AB
Ulf Tollaksen	Triventus

The project is divided into eight subtasks. They are strongly linked and are all aiming in increased total understanding of flows inside and around wind farms. Some subtasks are focusing on fundamental understanding, some are more applied and some are on the edge to implementation that can be used by the industry in the near future. The project is also active in a number of international projects related to a number of these subtasks. Table 1.2 gives an overview of the subtasks.

Table 1.3: Nordic Consortium Subtasks

Subtask	Title	Financer	Subtask Resp.
1	Instability and Interaction of WTW (Sim)	Swedish Energy Ag.	S. Sarmast
2	Instability and Interaction of WTW (Exp)	Swedish Energy Ag.	Y. Odemark
3	Optimization and Control of Large WF	VindForsk III	K. Nilsson
4	Optimization	Danish R. C.	S. J. Andersen
5	IceWake	TRI	G. Teneler
6	Optimization and control of wind farms	VindForsk III	I. Carlén
7	FarmFarm	VindForsk III	O. Eriklsson
8	IEA Projects	VF III, Swedish E. A.	S.-P. Breton

1.3 Status and development - a ten year perspective

The work within this three years project has been a continuation of previous work by Ivanell and Henningson in a close collaboration with DTU within the CFD area and Ingemar Carlén et.al. in the structural dynamics area. Ten years back, CFD applied to wind energy was in its very early stage. No work had been conducted successfully in Sweden at that point. There was however long experience in the structural dynamics field in Sweden which had grown from a number of early large scale wind power turbine projects in Sweden. At that point it was however not realistic to couple CFD with aeroelastic models. Today, about ten years later, after one finished PhD project, a number of PhD projects ongoing and a close collaboration with industry, the knowledge in the field has increased dramatically. Today we are in a stage where the CFD models to a great accuracy can estimate power performance in large wind farms. The structural dynamics models have also become much more reliable and we are close to a technical breaktrough where CFD and aeroelastic codes can be coupled. This has partly been done by other international groups but not to a full extent. A coupling between meso- and micro-scale models is also an area where the development is very fast since the need for interaction between these scales is clear when analyzing farm-farm interactions. When investigating farm-farm interactions one is also on the forefront of what is possible with todays computational resourses. The Nordic consortium does today access a cluster containing 16 000 CPU:s for their simulations. In the near future it it will also to possible to perform full farm simulations with the more accurate actuator line model instead of actuator disc models that are used today. Today actuator line models are used up to about 5 turbines maximum. (See explanation on the actuator line and disc model in chapter 1.5.)

1.4 Subtask Overview

Here follows a short summary of how the different subtasks relates to each other. In coming chapters, each individual subtask is described more in detail.

Subtasks 1 and 2 are investigating fundamental issues related to the spiral vortex system, i.e., how the stability of the tip vortex system and its breakdown is related to the length of the wake. In subtask 1 these fundamental issues are studied by the use of numerical simulations. Subtask 2 instead studies the same phenomena using an experimental setup. The same setup is used both experimentally and numerically. New blades have been designed to ensure that the aerodynamic parameters are identical in both the experimental and numerical setups.

The fundamental understanding of which parameters that affects the wake length etc. given by subtasks 1 and 2 are required in other more applied subtasks. Subtasks 3 and 4 are dealing with simulations of large wind farms while subtasks 1 and 2 are dealing with a limited number of turbines. Subtask 3 and 4 are using very large numerical simulations to investigate how to optimize the production and minimize the loads. To be able to do an optimization, new control mechanisms are developed within subtask 4.

Subtask 5, IceWake, is a part of a larger project ICEWIND financed by Top Research Initiative (TRI). ICEWIND contains a number of participants in Sweden, Denmark, Norway, Iceland and Finland. However, only one work package (WP3 in ICEWIND) deals with wakes and is therefore included as a subtask in the Nordic Consortium. The subtask is focusing on wakes and meso-micro scale interaction. It contains participants from Sweden and Kjeller Vindtekknik in Norway. One part of subtask 5 is strongly related to subtasks 3 and 4 but with the special interest of how icing effects the production in large wind farms. Moderate icing does result in small local derating of power output which has a close relation to how control and optimization is performed in subtask 4. Another part relates strongly to subtask 7, FarmFarm, since mesoscale simulations are also performed in collaboration with Kjeller Vindtekknik. Comparison with commercial software is also included into this subtask in collaboration with the Norwegian company WindSim.

Subtask 6 is the most applied project where knowledge from subtasks 1-5 is implemented into engineering approaches that could be used in the near future by industry. The work in the task is mainly performed by the consulting firm Teknikgruppen, which is the leading SME in the area of windpower technology. Time dependent large scale simulations are here transferred to fast simplified engineering method but with a base in results from very complex investigations. There is a strong interaction between subtasks 3, 4, 5, and 6 since engineering models are calibrated with advanced numerical models. These advanced numerical models are also based on fundamental understanding of the spiral system from subtasks 1 and 2.

Subtask 7 takes the next step in simulation complexity and is focusing on farm farm interactions that are becoming of large interest since large wind farms are erected in closer and closer vicinity with time. Subtask 7 therefore needs not only knowledge from subtasks 1-4 but also knowledge regarding how micro-scale simulations could be linked to meso-scale simulations. This study has been included in subtask 5 where also Kjeller Windtekknik is involved.

We apply our methods mainly on the Lillgrund Wind Farm. Lillgrund is a special case with very close turbine spacing and extensive measurements from the site is provided to the consortium from Vattenfall. This makes Lillgrund a suitable farm for validation of new models including both production and load simulations. A baseline report was formulated, [22] at the start up of the project, which indicated state of the art simulations of Lillgrund at the start of this project, and will therefore show the progress during the Nordic Consortium project and also indicate the accuracy of codes that are used by industry compared with state of the art research. The baseline study compares simulations of Lillgrund wind farm using a RANS model and a LES model. In both models, the turbines are represented using an actuator disc method. The simulation results are presented as power production and are compared with measurement data. The results show that the RANS model largely overestimates the wake deficit while the LES results show an almost perfect agreement with the measurements.

1.5 Numerical Methods used

Considering the above, there is obvious need for understanding and modeling the wake behavior of wind turbines. Wakes behind wind turbines can be distinctly divided into the near and the far wake regions. The study of near wake aerodynamics concerns the description of the vortices in the wake and their relation to the blade loading and inflow conditions. The near wake is followed by the far wake where the focus is put on the influence of wind turbines in farm situations and the modeling of the actual rotor is less important. In the far wake, turbulence models, wake interaction and topographic effects are of primary interest.

This section gives a short background of methods and codes used within the project. The main methods that are used are the actuator disc and the actuator line methods. They are chosen depending on to what level of detail one is investigating the flow structure and what area is being investigated, i.e., the near or the far wake downstream of a wind turbine rotor. Here the near wake is defined as the area just behind the rotor, where the properties of the rotor can be discriminated by the vortices in the wake. Thus the number of blades, the blade aerodynamics and the tip/root vortices are intrinsic elements of the analysis.

The main problem of utilizing CFD methods for simulating wake flows, however, is the need for resolving many different length scales, ranging from the thickness of the blade boundary layer to the diameter of the rotor. When considering wind turbine clusters or complex terrain conditions it is also important to handle length scales covering the distance between the turbines and the size of the atmospheric boundary layer. In practice it is necessary to focus on specific parts of the problem and/or to make some simplifying assumptions regarding the detailed behaviour of the problem. Typically, models coping with clusters of wind turbines are divided into simplified models or models in which the full Navier-Stokes equations are combined with actuator discs to represent the loading.

One of the limitations of the actuator disc method is that it does not take into account the individual presence of the blades. The individual vortices resulting from the presence of the rotor blades are therefore not modeled by this method, which rather models a vortex sheet trailing from the disc. Therefore, one cannot follow individual spiral vortices and their breakdown in the simulations using this method. To circumvent this problem an extended three dimensional method, the Actuator Line Method (ACL), was introduced by S ørensen and Shen, [36], in which body forces are distributed along lines representing each of the blades.

Both ACD and ACL method use a special technique to represent the blade. The geometry of the blades is not present. The benefit of that is that there is no need for a complicated mesh and no need to resolve the boundary layer on the airfoils. Instead the blades are represented by body forces calculated from airfoil data. The result is a very efficient method where the blade aerodynamics is well represented without the need of the complicated geometry. For more details about the numerical methods we refer to Mikkelsen, [20], and Ivanell, [9].

In this project, an implementation of the actuator line and disc in the EllipSys3D code is mainly used. For comparison other codes, such as WindSim and OpenFoam are used as well. EllipSys3D is a general purpose 3D solver developed by N.N. S ørensen and Michelsen, [37], [18], [19]. The flow solver is based on a finite volume discretization of the Navier-Stokes equations and in general curvilinear coordinates using multi-block topology. The code is formulated in primitive variables, i.e., pressure and velocity variables, in a collocated storage arrangement. Rhie/Chow interpolation is used to avoid odd/even pressure decoupling and the main solver is based on multi-grid techniques.

The computations are carried out as large eddy simulations (LES) employing the mixed sub-grid-scale model developed by Ta Phuoc, [38]. This model exploits the advantage of a closure combining vorticity and turbulent kinetic energy. In this model the vorticity is derived directly from the filtered variables whereas the turbulent kinetic energy is determined by use of a test-filter that is twice as coarse as the computational grid. For more details about the mixed scale model we refer to the text book by Sagaut, [26].

The averaged wind shear conditions that the turbines operate in are imposed at the inflow boundary. However, the numerical ability of flow solvers generally does not preserve this desired wind shear profile through the entire domain. In order to impose any wind shear profile, which may include directional changes with height, the flow field is initially generated applying momentum sources everywhere in the domain; see Mikkelsen et al., [21]. The magnitude of the computed momentum sources is generally very small. A power law wind shear profile with an exponent of 0.15 is chosen.

The influence of atmospheric turbulence is simulated by using a technique where turbulent fluctuations are imported in a 2D plane upstream the rotor from a pre-generated field which the flow solver then convects downstream towards the actuator discs or lines. All pre-generated turbulent fields are generated by the Mann model, [15], [14], [16].

Chapter 2

Subtask 1. Stability and interaction of wind turbine wakes - Simulations

2.1 Aim of subtask 1

The aim of the project is to understand the basic mechanism of formation and breakdown of the wind turbine flow structure. Breakdown of wind turbine wake has an important role to understand the interaction of wind turbine wakes. To obtain a better understanding of the properties of wakes generated by wind turbine rotors, a numerical study on the near wake structure, stability of the tip spiral and the interaction of two inline wind turbine has been carried out. The results will be compared with experiment work in the same area in subtask 2.

The method so-called actuator line (ACL) method is is a fully three-dimensional and unsteady aerodynamic model for simulating the wake of wind turbines. The flow field around and downstream the wind turbine is governed by the full three-dimensional incompressible Navier–Stokes equations, while the influence of the rotating blades on the flow field is computed by body forces acting on the blades. The forces are determined using the blade element method (BEM) combined with tabulated airfoil data. Body forces are distributed radially along lines representing the blades of the wind turbine and the forces are smeared among neighboring node points in a 3D Gaussian manner in order to avoid numerical singular behavior and mimicking the chord-wise pressure distribution. ACL method can resolve the wake dynamics, and thus the induced velocity downstream the rotor plane can be evaluated. The method is implemented into the EllipSys3D code developed in collaboration between DTU and Risø. This method opens new possibilities for wind turbine simulation with a well-resolved wake, as there is no need to resolve boundary layer of actual wing geometry.

2.2 Subtask description

The project is divided into three tasks; task one is concentrated on stability investigation of single wind turbine wake. Task two focuses on the wake interaction of two inline wind turbines and task three is the comparison of the near wake structure of the actuator line and vortex method.

2.2.1 Subtask 1.1 Non-linear stability investigation of single wind turbine

This task focuses on the stability of shed tip vortices and the process of how they breakdown by using a technique where two controlled type of perturbations are applied in the neighborhood of the basic spiral wake; harmonic and white noise perturbations. The amplification of waves traveling along the helix triggers some modes, leading to instability growth. Consequently the wake breaks down and more turbulent flow is observed further downstream.

Dynamic mode decomposition (DMD) and Proper Orthogonal Decomposition (POD) are utilized for analysis of the wind turbine near wake. This method allows for extraction of dominant coherent structures from the flow, leading to an improved understanding of the flow physics and underlying instability mechanisms. The modes extracted from the flow field can be analyzed individually instead of analyzing the full 3-D turbulent flow.

2.2.2 Subtask 1.2 Interaction of two inline wind turbine

This task focuses on the computation of two inline modeled wind turbines. NOWITECH/NORCOWE organized a "blind test two" workshop in which two inline wind turbine were studied experimentally and the main goal of the workshop was the evaluation of the numerical prediction of the wind turbine performance and its wake development through comparison with experiments.

2.2.3 Subtask 1.3 A comparison between an analytical vortex model and actuator line simulations of near wake wind turbine

This task focuses on comparison of analytical vortex model with the numerical simulation of an isolated horizontal axis wind turbine (simulated with the actuator line approach) to assess whether the predictions by the vortex model, that depends only on four parameters (the number of blades, the tip-speed ratio, the average circulation along the blade and the vortex core size) can be a substitute of more expensive CFD approaches. The model is based on the constant circulation along three blade (Joukowsky rotor) and it is able to determine the geometry of the tip vortex filament in the rotor wake, allowing the free wake expansion and changing the local tip-vortex pitch.

2.3 Results

2.3.1 Subtask 1.1

To determine the stability properties of wind turbine wakes a numerical study on the stability of the tip vortices behind the Tjæreborg wind turbine has been 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 and the tip vortices.

The wake breakdown is induced by disturbances applied to the tip vortices downstream of the blade. The amplification of waves traveling along the helix triggers some modes, leading to instability growth. A controlled way of disturbing the helical vortices is introducing low amplitude perturbation on top of the base flow. The basic flow and the wake breakdown is shown in Fig. 2.1. We choose low-pass filtered noise via a volume force, $\mathbf{F}_z = a\mathbf{F}(x,t)$, where a is the amplitude and $\mathbf{F}(x,t)$ is the generated excitation. We introduce a perturbation of amplitude $a = 0.005$ near the rotor tip, only in the axial direction, that assure the nonlinear effects occur far downstream. The grid configuration and the applied perturbations dictate the symmetric and non-symmetric conditions. Table 2.1 shows different configurations that result in symmetric condition (Case 1–4) and symmetry condition is breaked by forcing different white noise excitation near the tip of each blade.

Two modal decomposition methods is utilized to extract the dominant coherent structures from the flow; Proper Orthogonal Decomposition (POD) and Dynamic Modes Decomposition (DMD). The proper orthogonal decomposition is concerned with finding eigenfunctions of the two-point spatial correlation tensor, whereas dynamic modes are eigenfunctions of the approximated linear evolution operator. The dominant POD modes are the spatial structures that contains the most energy of the

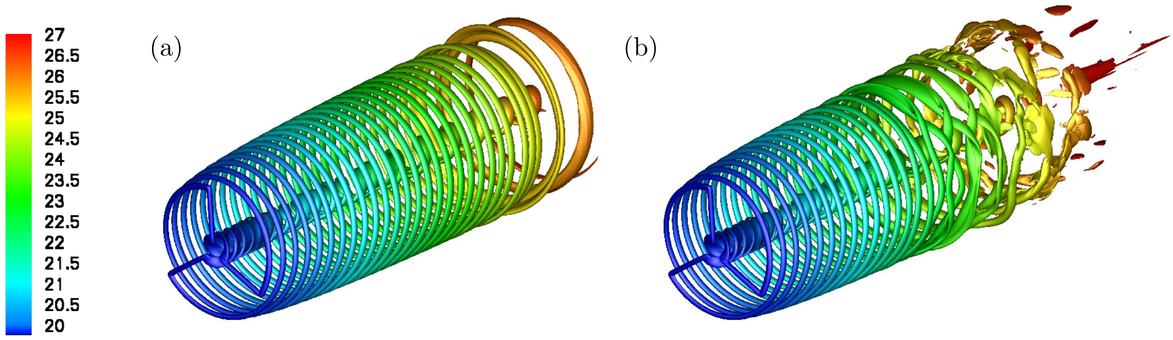


Figure 2.1: Isosurfaces of vorticity magnitude colored by streamwise position. (a) Basic steady state. (b) Helical vortices breakdown under influence of noise perturbations amplification.

Table 2.1: Stability analysis cases

Case	Polar domain	Excitation type	Excitation at the blade tip	Symmetry condition
1	one third*	single frequency	-	symmetry
2	one third*	white noise	-	symmetry
3	full	single frequency	similar	symmetry
4	full	white noise	similar	symmetry
5	full	white noise	non-similar	non-symmetry

* together with periodic boundary conditions

flow while, DMD modes are spatial coherent structures that oscillate at a given frequency ranked by their relative importance. The dissection of the flow field into subdomain allows us to concentrate on localized phenomena. The length of the subdomains and their positions are important parameters to study two phenomena in the wake: the mechanism of instability onset, and the nonlinear effects on wake breakdown. Considering the mechanism of the onset of instability, a linear wake subdomain is introduced where the mutual interaction of the tip spiral is not observed. By analyzing the temporal flow fields by the modal decompositions method on the linear sub-domain of the symmetric cases (Case 1–4), it indicates that two groups of modes are dominant in the wake, the low frequency and high frequency groups corresponding a wavenumber of 3/2 and 9/2 in one revolution. Examining modes in Fig. 2.2, it is shown that the high energetic temporal modes have the highest spatial amplification. This result were in agreement with previous stability of helicoid where the maximum spatial growth rate occurs at wavenumbers $\omega = 3 \times (k + \frac{1}{2})$ for all integer k. The comparison between the symmetric cases reveals that the one third domain does not limit any mode leading to instability growth.

Similar analysis of non-symmetric case 5 identifies six group of modes, with the wavenumbers of 1/2, 3/2, 5/2, 7/2, 9/2 and 11/2 in one revolution, see Fig. 2.3. This case shows that breaking the symmetry can lead to superposition of the unstable leading modes of one-bladed and three-bladed wind turbines where the maximum spatial growth rate of the single bladed wind turbines occurs at $\omega = (k + \frac{1}{2})$ for all integer k and similarly for 3-bladed wind turbine happens at $\omega = 3 \times (k + \frac{1}{2})$ for all integer k, see Fig. 2.4. This does agree well with previous work by Leishman et al. [13, 2, 1] The stability result is presented in [28, 32, 29].

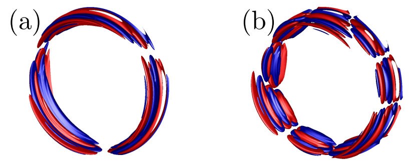


Figure 2.2: Symmetric POD modes (Case 4), a) low frequency and b) high frequency groups corresponding a wavenumber of 3/2 and 9/2 in one revolution.

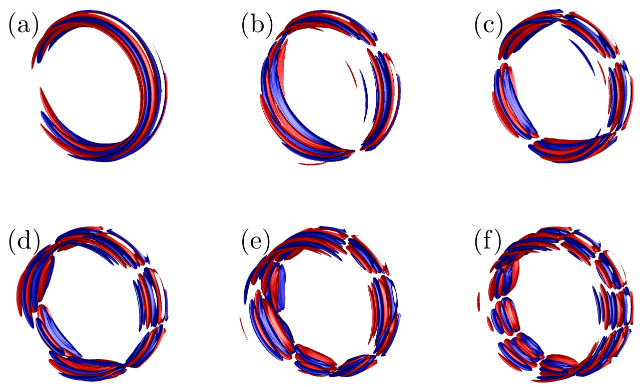


Figure 2.3: Non-symmetric POD modes (Case 5) with the wavenumbers of a) 1/2, b) 3/2, c) 5/2, d) 7/2, e) 9/2 and f) 11/2 in one revolution.

From the fundamental understanding of how a specific perturbation frequency grow along the spiral, i.e., how fast the perturbation starts to oscillate the tip spiral system and eventually result in a break down of the spiral system, one can derive a relationship between frequency, amplitude and the wake length. Figure 2.5 illustrates that the growth rate is the same regardless of the amplitude applied in the perturbation of the system.

When setting the maximum amplitude to A_m one can express the relation:

$$\frac{A_m}{A_0} = e^N = e^{\sigma_m \tau} \tag{2.1}$$

where A_m is the maximum amplitude and A_0 is the initial amplitude. N is the exponential growth factor which could be defined by maximum growth rate, σ_m, times the vortex spiral length, τ.

N could further be defined from the graph to be:

$$N = -3 - 3logT_u \tag{2.2}$$

where T_u is the turbulence level, i.e., u_{rms}/U when assuming that the initial amplitude is related to the turbulence amplitude, i.e., $A_0 \approx T_u$.

This gives:

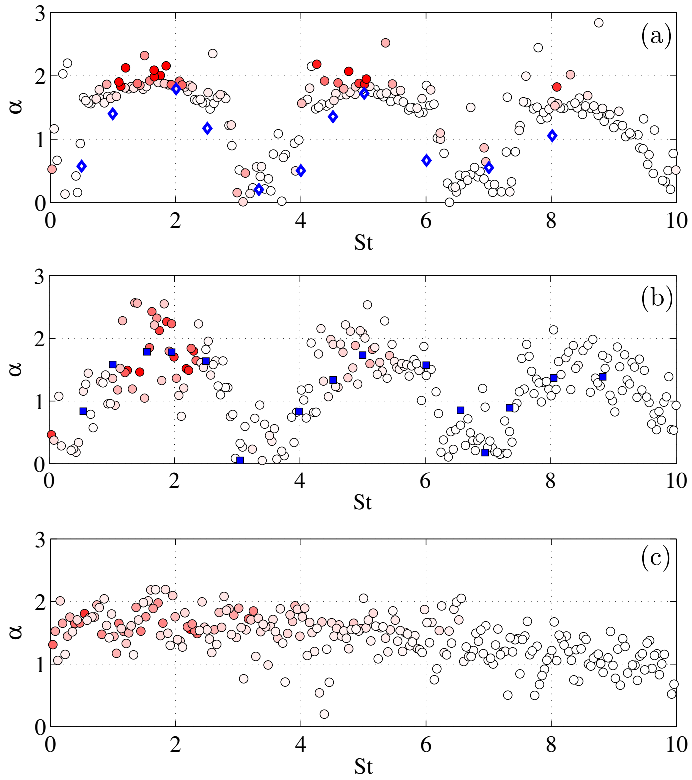


Figure 2.4: Spatial growth rate as function of Strouhal number, a) symmetric, (Case 1,2) b) symmetric, (Case 3,4) c) non-symmetric (Case 5). Circles correspond to leading modes based on DMD analysis. The blue diamonds in a) are stability analysis of the nonlinear simulations of the one third domain and the blue squares in b) are the nonlinear stability analysis of the full polar domain.

$$\tau = \frac{1}{\sigma_m}(-3 - 3logT_u) \tag{2.3}$$

which is the relationship between wake length and turbulence intensity when defining the wake length to correspond the length until the spiral system reaches non-linear behavior, i.e., the starting point for the pairing of tip vortices.

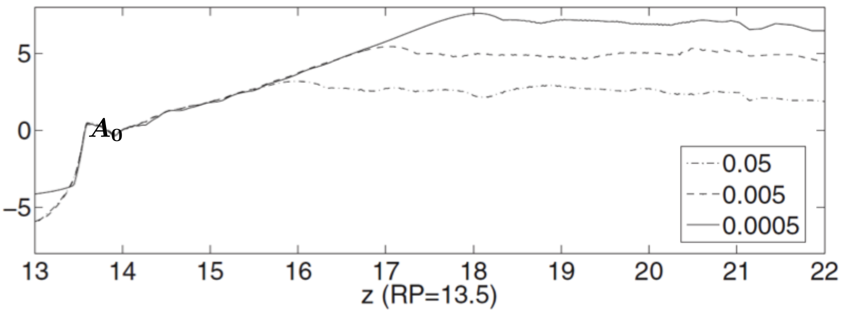


Figure 2.5: The figure illustrates the growth of the instability using different perturbation amplitudes. The turbine is positioned at z=13.5 where the scale on the z-axis correspond to the turbine radius. The vertical axis show the energy in logarithmic scale.

2.3.2 Subtask 1.2

This task is a part of Blind test 2 workshop computation for two modeled inline wind turbine. The Navier-Stokes computations were carried out using the 3D flow solver EllipSys3D. This code solves the discretized incompressible Navier-Stokes equations using a block structured finite volume approach. The flow field around the wind turbine rotor is simulated using the actuator line technique. In this model, the three-dimensional Navier-Stokes equations are solved with body forces distributed along rotating lines representing the blades of the wind turbine. The flow field is thus determined by solving the three-dimensional Navier-Stokes equations using LES, whereas the loading on each blade is computed by calculating the local angle of attack to determine the local forces from tabulated airfoil data. The forces on the flow as generated by the rotor are represented by rotating actuator lines and the rest of the flow is resolved using the Navier-Stokes equations on a very fine mesh. The provided input airfoil data for the ACL methodology is obtained from the in-house developed viscous-inviscid interactive code Q^3ucik. The computations is carried out at a Reynolds number of 10^5 using a free transition model and they showed that the S826 airfoil at low Reynolds number is subjected to static stall hysteresis. The higher lift and drag values are obtained at increasing incidences whereas, the lower lift and drag coefficients are computed at decreasing incidences.

The computational domain is a regular Cartesian grid, divided into a number of blocks. The grid is composed by a total of 42.46 million mesh points (32^3 points per each block) with the rotor represented by 43 points along each blade. High resolution grid are needed in order to capture gradients and to resolve the wake. The boundary conditions are the constant inflow velocity and convective outflow. The wind tunnel walls are included using slip boundary conditions. The wind tunnel turbulence is modeled by introducing the synthetic resolved turbulent fluctuations at $1.5D$ upstream of the first wind turbine. The development of the tip spiral and the effect of synthetic turbulence is observed in Fig. 2.6 and Fig. 2.7.

The power and thrust coefficients of both turbine were not in agreement with the experimental data for different range of tip speed ratios. Analyzing the wake deficit and the turbulence intensity profiles shows that the agreement between CFD and experiments would be better in the downstream positions. The solution of CFD would normally be considered very accurate, but the accuracy in the wake also depends on the modeling of the rotor loads and the input blade data. This is a sign that the first prediction should be repeated with more reliable blade data. This task is presented in

[31, 30].

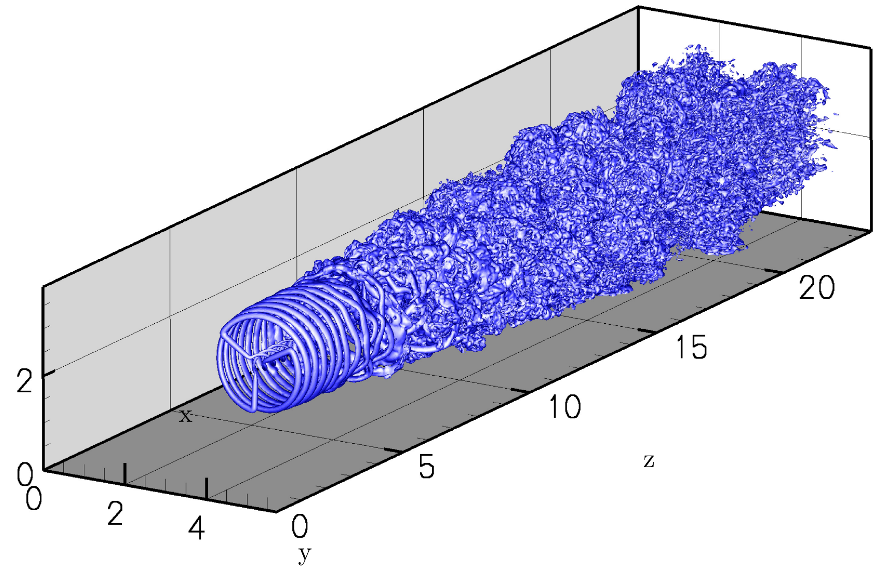


Figure 2.6: Development of the wake spirals are shown by the instantaneous vorticity magnitude Iso-surfaces.

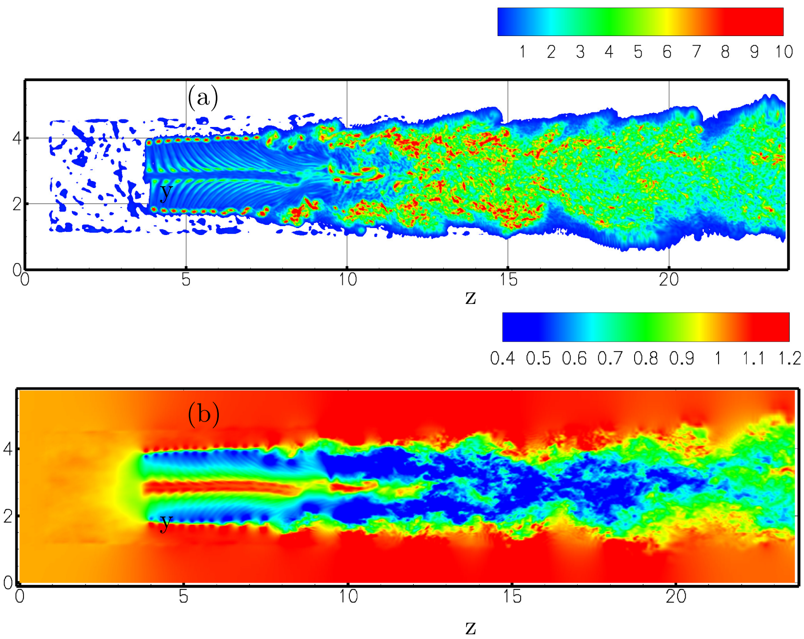


Figure 2.7: $y - z$ plane shows the development of wake spirals by the contour of a) instantaneous vorticity magnitude and b) streamwise velocity.

2.3.3 Subtask 1.3

The flow around an isolated horizontal axis wind turbine is estimated by means of a newly vortex code based on the Biot-Savart law, corrected for finite vortex core effects, with constant circulation along the blades. The results have been compared with numerical simulations where, the turbine blades are replaced with the actuator lines. Two different wind turbines have been simulated: one with constant circulation along the blade, to replicate the vortex method approximations, and the other with a realistic circulation distribution, to compare the outcomes of the vortex model with real operative wind turbine conditions (Tjæreborg wind turbine. The vortex model matched the numerical simulation of the turbine with constant blade circulation in terms of the near wake structure and the local forces along the blade. The simple vortex code is therefore able to provide an insight in the prediction of the flow around the wind turbine similar to the actuator line code but with a negligible computational effort. The results from the Tjæreborg turbine case showed some discrepancies between the two approaches but overall the agreement is qualitatively good, validating the analytical method for more general conditions. This task is presented in [33].

2.4 Conclusions from subtask 1

To determine the stability properties of wind turbine wakes a numerical study on the stability of the tip vortices behind the Tjæreborg wind turbine has been 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 and the tip vortices. The flow is then perturbed by inserting excitation leading to wake breakdown. The excitation and grid configuration both symmetry and non-symmetry case is forced and by analyzing the temporal flow fields by the modal decomposition (DMD) method, it indicates that groups of modes are dominant in the wake, 2 group of frequencies in symmetric case and 6 group of frequencies in non-symmetric cases. Examining these modes it is shown that the high energetic temporal modes have the highest spatial amplification.

From the fundamental understanding of the wake structure, a mathematical model for relationship between ambient turbulence level and the wake length has been established.

Comparison of the numerical simulation and experiments of the two modeled inline wind turbine shows that the input blade data has an important role in correct prediction of the power and thrust coefficients and in the downstream position, the discrepancies between numerics and experiments is decreased.

Comparison of the near wake structure of a vortex model and ACL approach shows that with extremely less computational effort the flow around the wind turbine can be correctly predicted.

Chapter 3

Subtask 2. Instability and interaction of wind turbine wakes - Experiments

3.1 Aim of subtask 2

Research on the stability of wind turbine wakes has previously mostly been done numerically (see e.g. Ivanell et al. 2010). There is a great demand for experimental data to be compared with and to complement existing numerical results. Enhanced knowledge of the behaviour of wind turbine wakes is also needed in the development of new wake models. Experiments with a small-scale model turbine has previously been done at KTH (Medici 2005), and this work has been continued in the present task. The main aims of task 2 are as follows:

- Increase the knowledge of the behaviour of wind turbine wake flows. Special focus lies on the development and stability of the wake, as well as the evolution and development of the tip vortices, that are shed from the turbine blades.
- Create a database of experimental velocity and turbine data that can be used for validation of numerical models.

3.2 Subtask description

Task 2 contains mainly wind tunnel measurements on a small-scale model turbine. The original turbine was manufactured by Jan-Åke Dahlberg at Vattenfall Vindkraft AB. A new setup for phase-locked measurements has been developed in task 2 and the existing model turbine has been complemented by the design and manufacturing of new turbine blades, which was done in cooperation with Dr. Robert Mikkelsen at Denmark Technical University. Velocity measurements in the wake of the turbine have been performed with hot-wire anemometry, a technique where the velocity can be measured with a very good resolution in both time and space. In order to characterize the model, also the rotational frequency, the power output and the total drag force on the model have been measured. The size of the model rotor radius was 89 mm and 113 mm for the two different sets of blades.

Two studies have been performed and are currently being reported (task 2.1 and 2.2). Two additional studies are at a planning stage and are being performed during 2013 (task 2.3 and 2.4).

3.2.1 Subtask 2.1 - Tip vortex evolution and stability

From each wind turbine blade, a tip vortex is shed due to the pressure equalization between the pressure and suction sides of the airfoils. The tip vortices from all three blades form a helical system of vortices in the near wake, immediately behind the wind turbine. The stability of this vortex system has previously mostly been studied numerically (see e.g. Ivanell et al. 2010 and Okulov and Sørensen 2007). To complement the numerical studies, the stability of the tip vortices were here studied experimentally, by introducing a secondary disturbance in the form of two pulsed jets. A new experimental setup for stability analysis was therefore constructed and successfully tested between December 2010 and June 2011. New turbine blades for the model were then designed and manufactured together with Dr. Robert Mikkelsen at Denmark Technical University in October 2011. Additional tests with the new blades were performed during March 2012. The experimental setup as well as the main results are described in the results section below.

3.2.2 Subtask 2.2 - Influence of forest turbulence on the outputs of a model wind turbine

As more and more wind power is being installed, many of the best sites for wind power are now occupied. Wind power plants are therefore now placed in areas of complex terrain; near mountains and hills and inside forests. The flow within the atmospheric boundary layer above a forest can differ substantially to that over a low vegetation region, and the effects on the power production and loads on a wind turbine is to the present date not well investigated. Task 2.2 contains a wind tunnel study on a model wind turbine placed inside a model forest, which in this case is modelled by cylindrical pins with a circular cross section. The effects on both the power production and the loads on the model turbine were studied for different turbine hub heights above the model forest. The turbine is here subjected to a shear inflow, i.e. an inflow velocity that changes with height. Also the turbulence level at hub height varies with the height above the model forest, which may have severe consequences when it comes to problems with fatigue. In a second stage, a new numerical model was developed, which takes the effects of the shear layer into account. The measurements and model development described above have been carried out in collaboration with Dr. Antonio Segalini at KTH Mechanics.

3.2.3 Subtask 2.3 - Wake interaction

The power losses in a wind turbine farm can be severe due to wake effects, and the additional loads on the individual turbines due to the increased turbulence levels can cause fatigue problems. The interaction between several wakes is therefore very important. In task 2.3, it is planned to measure the velocity field behind two turbines. The position of the second turbine can be varied, both spanwise and streamwise, and the effects on the wakes can be studied. It is planned to use a velocity measurement technique called Particle Image Velocimetry, where the instantaneous velocity in a plane can be captured simultaneously. By capturing two velocity components simultaneously, it is possible to look at wake structures and make velocity field decompositions. Task 2.3 is planned to be performed in the spring of 2013.

3.2.4 Subtask 2.4 - Wake development and comparison with numerical models

The velocity field and the development of the wake behind the model turbine has already been measured as a part of task 2.1. The streamwise velocity was measured across the wake at several different downstream positions, for both blade types and different free stream velocities and tip speed ratios. This data will in task 2.4 be compared with numerical simulations, in the first stage Actuator

Disc (ACD) computations. Here, the measurements of the thrust force from the model will be used as input for the ACD computations, where this information is used to model the turbine by a body force. Since no blade geometry is used, the computations are fairly fast and computations can be made for all the measured cases. Task 2.4 will be performed during 2013.

3.3 Results

In the following section, only a part of the most fundamental results from the measurements will be presented, mainly regarding the testing of the model and the experimental setup.

For stability measurements and analysis, it is crucial that the "same" event can be repeated multiple times. In order to create temporally synchronized data, the measurements need to be phase-locked to ensure that the same event is captured each time. For the present measurements, there are three key events that need to be included in the triggering signal:

1. The passage of a pre-marked blade.
2. The added disturbance frequency.
3. The vortex shedding which is often present around small-scale model turbines, and causes a shift of the wake from side to side.

To be able to trigger on all of the three items mentioned above, a non-inverting adder was built, which could add the three signals. The sum of the signals then constituted the triggering signal, and when it reached a certain predefined level, the measurements were started. The added disturbance was in the form of two pulsed jets, one on each side of the nacelle. The orifices of the jets were connected to small tubes, which in turn were connected to a high-pressure accumulator tank via two fast-switching valves. By controlling the frequency of the fast-switching valves and the pressure in the accumulator tank, the frequency and amplitude of the disturbance could be adjusted. The results from the stability analysis show that the tip vortices are fairly insensitive to the disturbance frequency, but more sensitive to the initial amplitude of the disturbance.

The power and thrust coefficients of a wind turbine are commonly defined as:

$$C_P = \frac{P}{\frac{1}{2}\rho U_\infty^3 A} \ , \qquad C_T = \frac{T}{\frac{1}{2}\rho U_\infty^2 A} \ , \tag{3.1}$$

where P is the power output, ρ is the air density, U_∞ is the free stream velocity, A is the rotor area and T is the total thrust or drag force. C_P and C_T are usually plotted as functions of the tip speed ratio λ, which is the speed of the tip of the blade divided by the free stream velocity:

$$\lambda = \frac{\omega R}{U_\infty} \ , \tag{3.2}$$

where ω is the angular frequency and R is the rotor radius. Examples of the measured power and thrust coefficients for the model turbine can be seen in Fig. 3.1. Results are shown for different pitch angles θ of the blades, ranging from 6 to 11°. Small-scale models usually perform worse than full scale turbines, with a smaller maximum power output and a larger thrust coefficient. For small-scale turbines, normal values for C_P are around 0.2-0.4 and for C_T 0.7-1.2. For a larger scale turbine, typical values of C_P and C_T are 0.4-0.5 and 0.6-0.8. Due to the small scale in the wind tunnel, the optimal tip speed ratio is also often lower than in full scale.

For both wind turbine blade design and for wind farm optimization, it is common to use the blade element momentum (BEM) method. It is based on momentum theory and discretizes the blade into

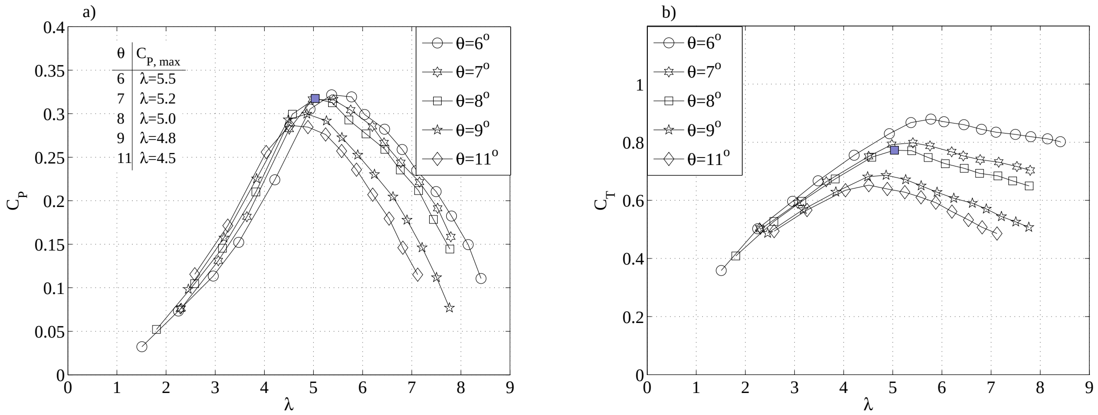


Figure 3.1: a) Power coefficient C_P and b) thrust coefficient C_T for the model turbine for different blade pitch angles θ, as functions of the tip speed ratio λ. The filled symbols at λ=5 corresponds to the optimal condition for which the blades were designed. The free stream velocity was 6.5 m/s.

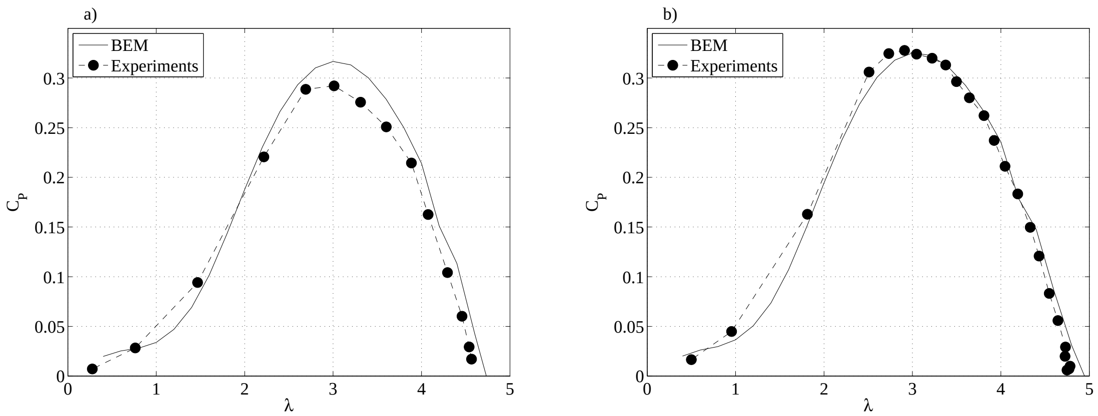


Figure 3.2: Comparison between the blade element momentum method and measurements on the model turbine. a) Free stream velocity 6.5 m/s and b) free stream velocity 10 m/s.

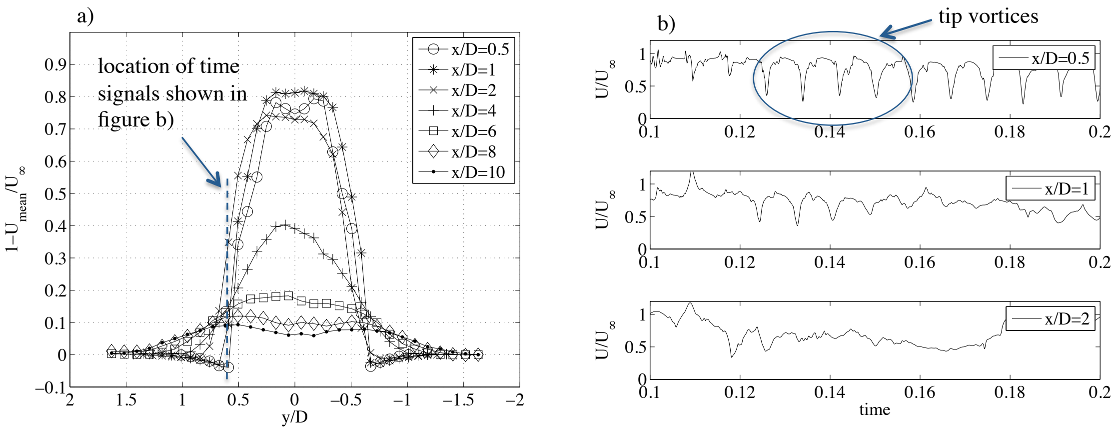


Figure 3.3: a) Mean velocity in the wake for different downstream locations. b) Velocity time signals at a location where the tip vortices can be seen.

a number of elements along the radius. A comparison between BEM and measurements is shown in Fig. 3.2.

The mean streamwise velocity U_{mean} in the wake is shown in Fig. 3.3a, as a function of downstream distance x/D, with D being the rotor diameter. The mean velocity deficit at e.g. 4 rotor diameters downstream is in accordance with field measurements done on a larger turbine (Trujillo et al. 2011). In Fig. 3.3b, examples of the velocity time signals are shown. The chosen position is at the edge of the wake region and for three different downstream positions. The tip vortices can be seen clearly in the most upstream position.

3.4 Conclusions

Several tests have been performed to characterize the model turbine behaviour. Different hub heights have been tested and as previously mentioned, two different types of turbine blades have also been used. Also the pitch angle of the blades has been varied, as well as the tip speed ratio and the free stream velocity. All cases have now been analysed, and some interesting differences have been discovered. The new experimental setup has been shown to work well and will possibly be used again at a later stage. Parts of the results from task 2.1 and 2.2 have been published in a Licentiate thesis (Odemark 2012), and was presented at a Licentiate seminar in May 2012. The thesis also includes a detailed description of the experimental setup and a summary of the results from the first 2.5 years of the project within task 2.

3.5 Future work

Subtask 2.1 is currently ongoing, one report regarding the new experimental setup is finished (one paper submitted for publication) and the report from the second measurement campaign is being written and is planned to be submitted for publication in January 2013. In a later stage, the data will also be used for comparison with numerical simulations using the Actuator Line (ACL) technique, which are performed in task 1.

The data from task 2.2 were presented at the conference *The Science of Making Torque from Wind* in Oldenburg in October 2012 and are being published in the conference proceedings. The additional numerical model is currently being reported in a paper and is planned to be submitted for publication in February 2013.

For task 2.3, a cooperation with the University of Gävle is being established, and it is possible to perform the measurements in a wind tunnel in Gävle in early 2013. This wind tunnel is somewhat larger than the ones at KTH and is therefore suitable for wake interaction studies.

Task 2.4 is planned to be performed during 2013.

Chapter 4

Subtask 3. Optimization and control of wind farms

4.1 Aim and background

The main objective of this task is to analyze the efficiency of large wind farms using numerical tools, and to compare and validate it with measurement data. It is also investigated if it is possible to improve this efficiency by manipulating the flow inside the farm. Today, the computations on large wind farms are restricted to large-eddy simulations (LES) using the actuator disc (ACD) method for turbine parametrization due to the availability of computational resources. The next natural step is to perform the simulations using the actuator line (ACL) method which is more physically complex. This method, however, is substantially more computationally demanding. The first phase of the task is to validate the different methods using measurement data. In connection to the LES/ACD computations, a power control method is implemented to better capture the real performance of each turbine.

4.2 Subtask description

Like stated, the task deals with LES computations of large wind farms. The task is divided into three sub tasks; LES/ACD wind farm simulation and validation, LES/ACL single turbine simulation and validation, and Implementation and validation of a power control method. The two former tasks are performed using the EllipSys3D code developed at DTU/Risø by Sørensen [37] and Michelsen [18][19]. Generally, both methods model the rotor using body forces which are determined by tabulated airfoil data. Thus, the boundary layer of the blades is not resolved and most of the computational power can be preserved for modeling the wake flow. The ACD method is described in detail in Mikkelsen [20]. The ACL method is described in Sørensen and Shen [36]. The latter task is performed using an in-house developed BEM code, which is based on the method described in Hansen [7].

4.2.1 LES/ACD wind farm simulation and validation

In this task, LES/ACD computations of the Lillgrund wind farm are performed. The task comprises a grid sensitivity study, a turbulence intensity (TI) sensitivity study, a comparison between measured and computed power performance, and a simple "optimization" study. The atmospheric conditions (AC) were measured prior to the establishment of the farm. Since there are no reliable measurements of the AC during the analyzed time period, i.e, during operation of the wind farm, the pre-measurements are used only as a frame for the AC imposed in the computations. The simple "optimization" study is performed by reducing the power outtake in the front row turbines, perpendicular to the inflow wind direction. This approach will allow more kinetic power to be transfered to the downstream turbines in the farm. The farm layout is depicted in Figure 6.3.

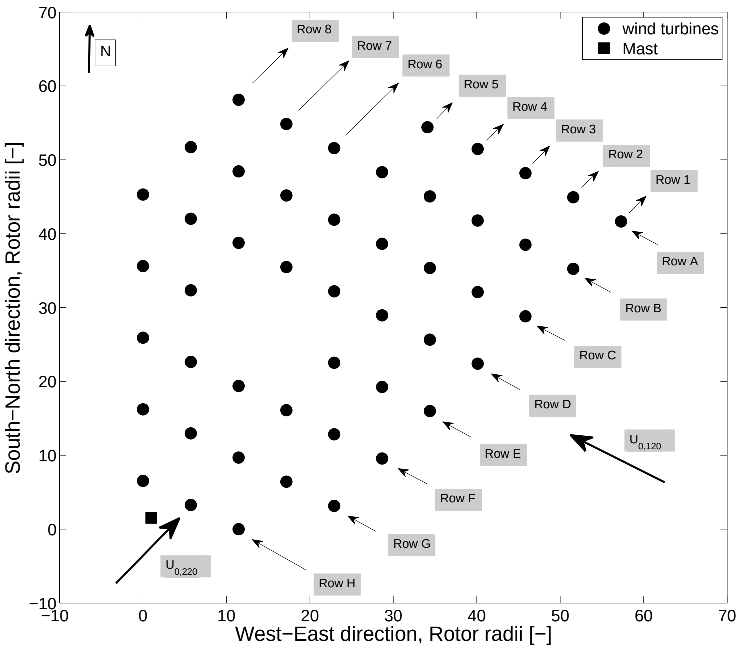


Figure 4.1: The layout of the Lillgrund wind farm. The axes are normalized with R. The different U_0 indicate the studied inflow angles.

4.2.2 LES/ACL single turbine simulation and validation

In this task, LES/ACL computations are performed on the experimental MEXICO wind turbine. Experimental data was measured on the actual turbine in a wind tunnel test case (the MEXICO project). The aim is to analyze how the near wake behaviour is captured using the LES/ACL method compared to the experimental case using PIV data. The studied parameters are tip vortex size, tip vortex core strength, bound circulation, streamwise and radial velocities as function of the downstream distance from the rotor and the streamwise and radial position of the tip vortex cores, i.e., the tip vortex trajectory. The study is based on five cases. In the first three, the rotor is perpendicular to the incoming flow and the tip speed ratio, λ, is varied so that $\lambda = 4.2$, $\lambda = 6.7$ and $\lambda = 10$. In the last two cases the turbine is operating with a yaw angle of $+30^o$ and -30^o, respectively, with $\lambda = 6.7$.

4.2.3 Implementation and validation of a power control strategy

In order to perform realistic simulations of a wind turbine, a control method which enforces the turbine to operate under optimal aerodynamic conditions is required. The method is in a first step implemented for conditions when the turbine is operating below rated power. The method makes use of the Newton's second law for rotating bodies and is implemented using the methodology described in Jonkman et al. [10].

4.3 Results and discussion

In this section the general results are shown and discussed for each sub task.

4.3.1 LES/ACD wind farm simulation and validation

The grid study is performed using grids with different resolution. The results show a very small difference between the grids. Due to limitations of computational resources, the medium sized grid is used for all further analyses. The numerical errors due to this grid are relatively small. This grid has a resolution of $0.1R$, where R is the rotor radius, in the inner equidistant region. The TI sensitivity study, using TI levels of approximately 5%, 7% and 10%, shows that, as expected, an increased ambient TI results in a faster wake recovery and thus a higher farm production. The effects are, however, relatively small inside the farm, where the turbine induced turbulence is found to be dominant. The results are compared to a 0% TI case. Here the production of the second and third turbines in each row is unrealistically low. Therefore, it is of great importance to impose a turbulent boundary layer, the level of the TI is secondary. For all further analyses the 7% TI level is imposed. The measured productions are extracted and averaged for the wind sectors of 120 ± 2.5^o and 220 ± 2.5^o, using a wind speed of $8 \pm 0.5m/s$. Therefore, simulations are performed for 117.5^o, 120^o and 122.5^o for the first wind sector and for 217.5^o, 220^o and 222.5^o for the second sector. Figure 4.2 shows the comparison for the different rows of turbines between measurements and computations for the 120^o case. In general the agreement between computed and measured data is excellent. Figure 4.3 depicts the comparison for the different rows of turbines between measurements and computations for the 220^o case. In this case, the power production is slightly overestimated in the computations compared to the measurements, but the general trends are very well captured. According to momentum theory it should be possible to maximize the production of a wind farm by adjusting the production of the individual turbines in the farm. As a first step, the front row turbines are de-rated. The study is performed by pitching the blades with 0^o, 2^o, 4^o and 6^o. The 0^o case represents the reference case. The production losses in the front row turbines are, however, for this case greater than the production gains in the second row for all pitch angles. Therefore, this simple "opimization" study has no positive effect on the farm efficiency.

4.3.2 LES/ACL single turbine simulation and validation

The near wake features of the MEXICO rotor are measured experimentally and determined numerically. The tip vortex size is about one order of magnitude larger in the computations compared to the measurement which is due to the coarseness of the grid used in the computations. However, the tip vortex strength and the bound circulation are found to be in the same order when comparing measurements with computations. The streamwise velocity as a function of the dowstream distance is found to be slightly overestimated in the computations. However, this difference is relatively small and the general trends are well captured. The radial velocity is well captured. The tip vortex trajectories are well captured for most of the cases which is shown in Figures 4.4 and 4.5. In the case when $\lambda = 10$, the biggest difference is found. In this case there are tunnel effects restricting the wake expansion in the measurement case which are not captured in the simulations.

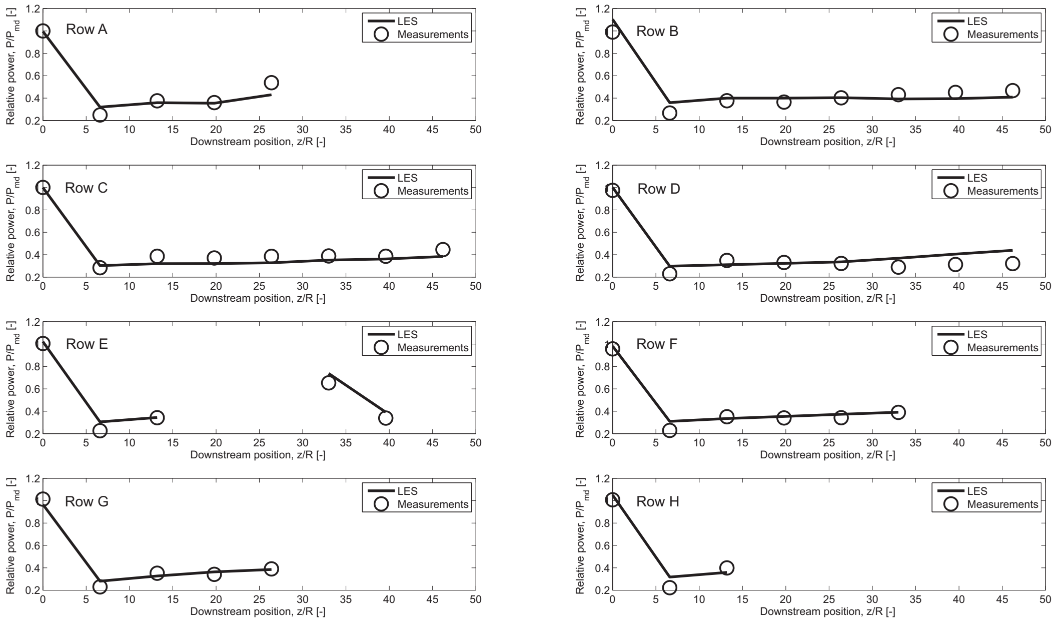


Figure 4.2: Computations compared with measurements for the inflow angle sector of 120 ± 2.5 deg and $U_0 = 8$ m/s (Row A-H). The production is normalized with the median of the production of the front row turbines.

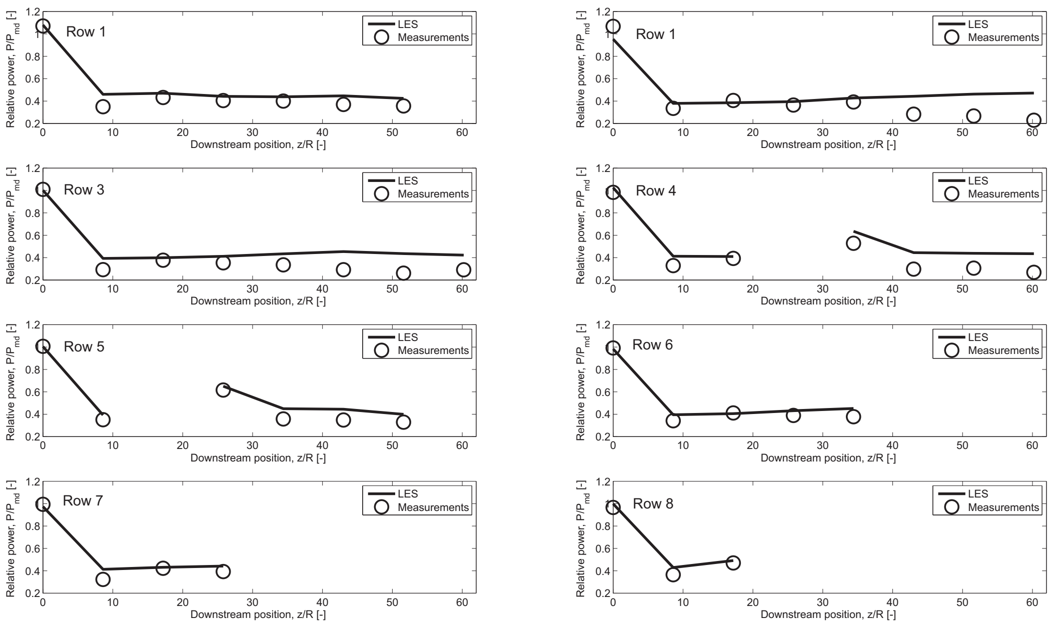


Figure 4.3: Computations compared with measurements for the inflow angle sector of 220 ± 2.5 deg and $U_0 = 8$ m/s (Row 1-8). The production is normalized with the median of the production of the front row turbines.

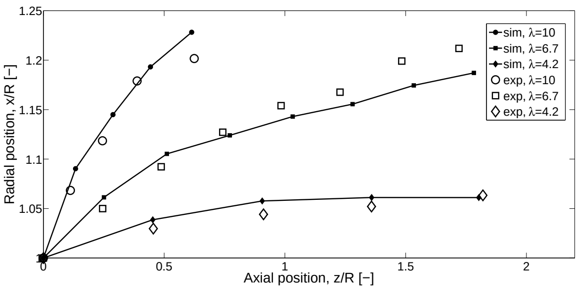


Figure 4.4: Tip vortex trajectory without yaw.

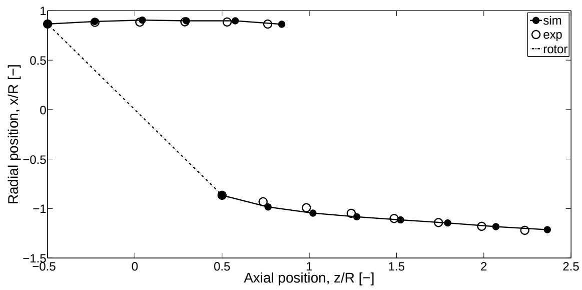


Figure 4.5: Tip vortex trajectory with yaw.

4.3.3 Implementation and validation of a power control strategy

Prior to this project, no power control method was implemented in the ACD method. In order to improve the method, a control method has been implemented. In this study, the method is tested using an in-house developed BEM code which is a modification of the method described by Hansen [7]. The control method is based on the Newton's law for rotating bodies. One of the inputs to the method is generator torque as a function of the angular velocity. This is determined according to the method described by Jonkman et al. [10] and the result is shown in Figure 4.6. Another input is the moment of inertia, I_D, of the drivetrain. The method is tested with different values of I_D and the results are shown in Figure 4.7. The expected result is achieved, the controller reacts faster to velocity changes and the C_P value is always closer to $C_{P,max}$ for lower values of I_D. The method is also tested by varying the inlet turbulence conditions while keeping the I_D fixed. Also here the expected result is achieved, for a less turbulent inflow, the angular velocity of the rotor follows the fluctuating inflow almost perfectly and for a more turbulent inflow, the general trend is well captured while peaks of the velocity are not captured. This is shown in Figure 4.8. Looking at the C_P, Figure 4.9, the less turbulent inflow allows the turbine to operate close to $C_{P,max}$ at all times while a more turbulent inflow gives significant peaks at all positions where the turbine is operating in non-favorable conditions. It is noted that the C_P never exceeds $C_{P,max}$. The control method is at this date already implemented in the ACD method in the EllipSys3D code, being tested and validated. Preliminary results show that the controller works as expected.

4.4 Conclusion and outlook - subtask 3

In the first part of the task, the power production in the Lillgrund wind farm was studied. Computations using large-eddy simulations with the actuator disc method were compared with measurements. The result showed a very good agreement between measurements and simulation results when atmospheric condtions are imposed. Furthermore, the effect of de-rating the front row turbines gives a loss in farm production for all studied cases. Future work will consider also de-rating of downstream turbines, as well as studying fatigue loads in the farm. Future work will also include the power control method.

In the second part of the task, the wake flow behind the MEXICO rotor was analyzed and used to validate the actuator line method. The analysis was based on five different flow situations, and the simulation results are compared to results based on PIV measurements performed on the MEXICO rotor. The tip speed ratio was varied for three of the cases and the rotor was yawed in two. Generally, a very good agreement was found when comparing the studied parameters (tip vortex core strength, bound circulation, streamwise and radial velocities as function of the downstream distance from the

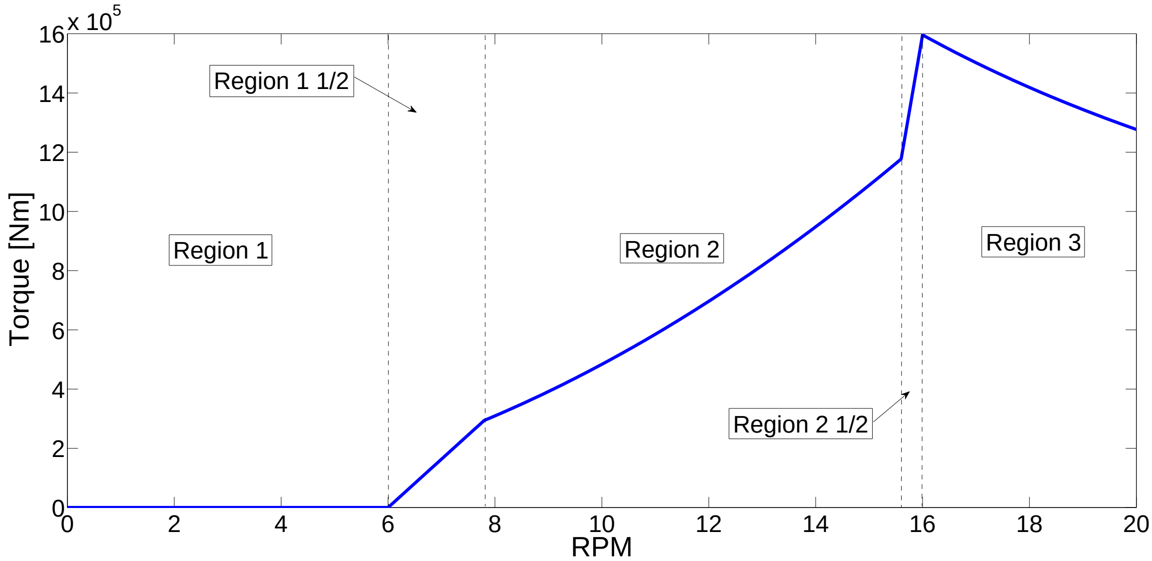
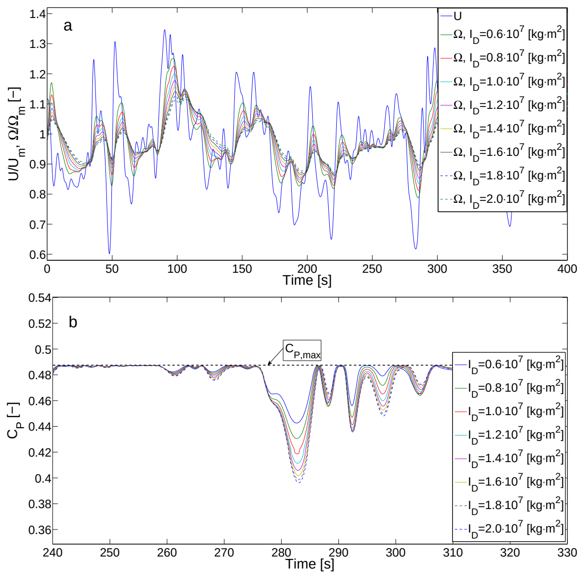


Figure 4.6: The generator torque curve created for the Siemens SWT-2.3MW turbine.



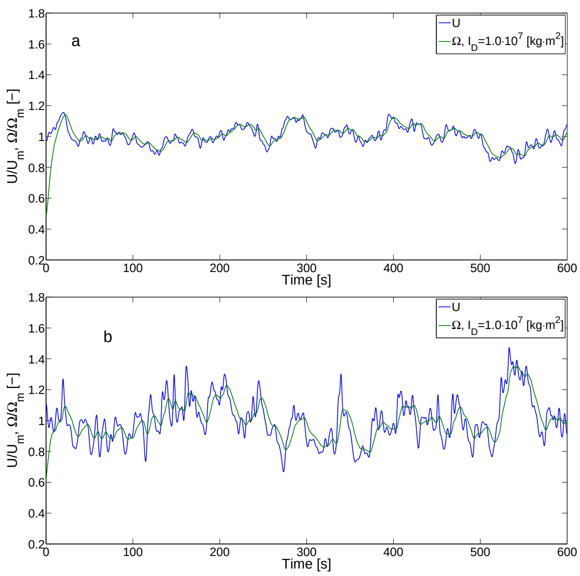


Figure 4.7: a) Normalized Ω curves for different values of I_D together with normalized velocity. b) C_P for different I_D as a function of time.

Figure 4.8: a) Ω and velocity curves for the minus $2D$ position. b) Ω and velocity curves for the $7D$ position.

rotor and the streamwise and radial position of the tip vortex cores, i.e., the tip vortex trajectory) determined in measurements and simulations. The tip vortex size was however found to be much larger in the simulations. The validation work will be used to improve the knowledge about how the results from ACL simulations are interpreted. Discussions within the MexNext Annex are currently

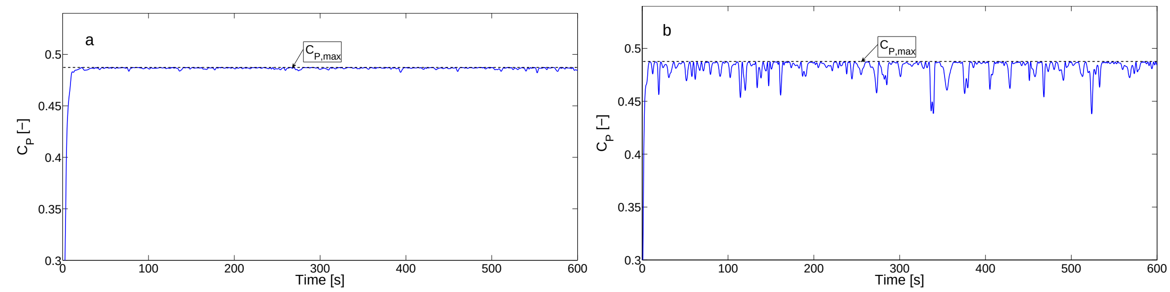


Figure 4.9: a) C_P curve for the minus $2D$ position. b) C_P curve for the $7D$ position.

being held and it is planned to establish a new measurement campaign. Future work will, if the measurements are available, be performed on the breakdown of the tip vortices in order to further validate the ACL method.

In the third part of the project, a power control method was implemented and tested in an in-house developed BEM code. The method was tested using different values of the moment of inertia and different inlet conditions. The method reacted as expected when varying the different parameters. The control method is at this date implemented in the actuator disc method in EllipSys3D, and will in the near future be tested thoroughly in this environment.

Chapter 5

Subtask 4. Optimization

5.1 Aim of subtask 4

The aim of subtask 4 is to investigate the wake behind wind turbines in order to gain knowledge on the turbulent wake structures. This knowledge will be used to develop tools which can be utilized in optimization studies for wind farm planning.

5.2 Subtask description

The task focusses on numerical simulations of wind turbines using the actuator line method and LES with the inhouse software EllipSys3D. Two main task have been concluded so far and is reported in the following.

5.2.1 Subtask 4.1

The wake development is investigated behind a single wind turbine as it develops downstream.

5.2.2 subtask 4.2

The wake inside an idealised infinitely long row of wind turbines is investigated and a reduced model is constructed by using the spatial modes and truncating the temporal eigenfunctions derived from a Proper Orthogonal Decomposition of the flow field.

5.3 Results - subtask 4

The results presented here focus on the POD analysis of the wake flow field. POD is a statistical method yielding an optimal linear subspace, optimal in terms of the variance of the energy content, i.e. it ensures that the sorted modes contain the most energitic states. POD is a proven method for examining coherent turbulent structures for stationary random processes.

POD can be considered as an energy filter and as such it is possible to construct a Reduced Order Model ($\widetilde{\mathbf{u}}$) based on the decomposition. The POD analysis gives both spatial POD modes ($\phi_{\mathbf{k}}$) and temporal eigenfunctions of the POD modes. Since the flow has approached a random stationary process the idea is to truncate the reconstruction even further, because the temporal eigenfunctions are composed of Fourier modes. The dominant frequencies of the temporal eigenfunctions can be identified through spectral analysis and by choosing an optimal combination of these dominant frequencies $f_{k,m}$ it is possible to reconstruct the flow field as follows:

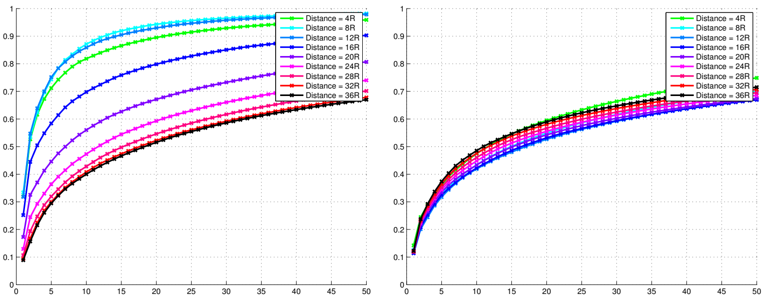
$$\mathbf{u_j} \approx \widehat{\mathbf{u_j}} \approx \widetilde{\mathbf{u_j}} = \mathbf{u_0} + \sum_{k=1}^{K} \phi_k \sum_{m=1}^{M} (\beta_{k,m}^{(1)} cos(2\pi f_{k,m} t_j) - \beta_{k,m}^{(2)} sin(2\pi f_{k,m} t_j)) \tag{5.1}$$

The coefficients $\beta_{k,m}$ are determined by optimising the reconstruction in a linear least square sense. Here, k denote the POD mode and m denote the frequency number for a given POD mode, sorted in terms of influence after the linear least squares fit. The reduced order model is applied for Task 4.2.

5.3.1 Subtask 4.1

The flow behind a single wind turbine is simulated to analyse the wake development as function of distance, up to $40R$ downstream. The incoming wind is taken as a uniform velocity profile corresponding to $10m/s$. A number of different Turbulence Intensities have been studied to investigate the effect of incoming turbulence on the wake development.

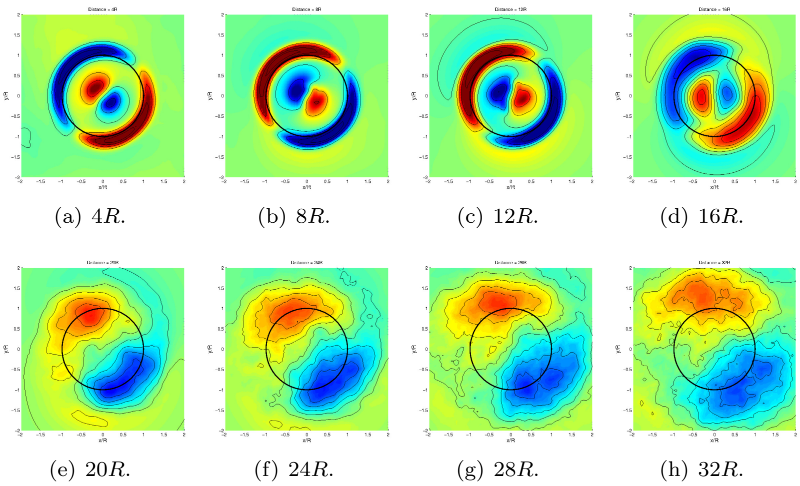
The POD coefficients as function of distance are shown Figure 5.1 for 0.1% and 11% TI. Clearly, the incoming turbulence has a significant influence on the POD modes and the energy distribution across the POD modes. Incoming turbulence means that there is only minor spatial redistribution of energy between the POD modes due to the earlier initiation of vortex breakdown in the wake. For the case with low turbulence intensity, the wake approaches the high turbulent case as the turbulent wake develops further downstream. Close to the wind turbine the flow is governed by a low number of POD modes.



(a) (b)

Figure 5.1: POD eigenvalues. (a) 0.1%TI. (b) 11% TI.

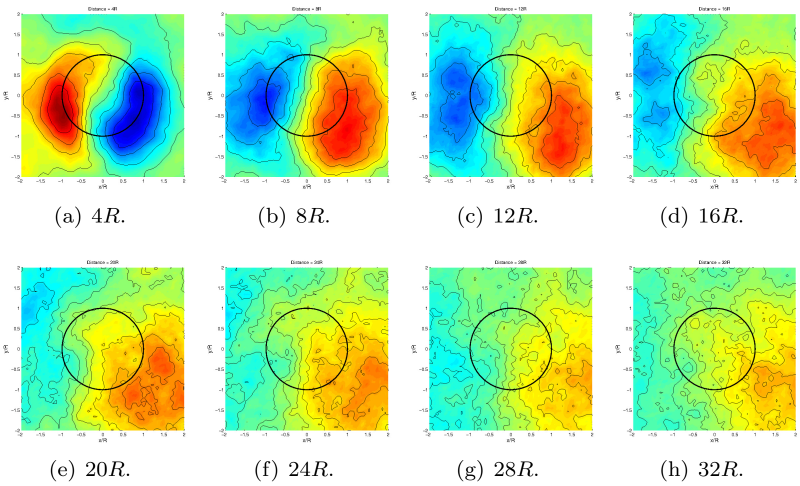
The spatial development with distance of the spatial POD modes is given in Figures 5.2 and 5.3 for 0.1% and 11% TI, respectively. The low turbulence case has very distinct dipolar POD modes in the wake center and where the tip vortices has folded into a vortex sheet. The dipolar behaviour is maintained downstream although the structures stemming from the root vortices eventually disappear. Similar behaviour is capture by the second POD mode, which is orthogonal and rotated 90°. The spatial POD mode pairs 3/4 and 6/7 portrait quadrupole and hexapole regions at the tip vortices, respectively. The high turbulence case consistently shows two regions, although it naturally becomes more and more turbulent downstream.



(a) $4R$. (b) $8R$. (c) $12R$. (d) $16R$.

(e) $20R$. (f) $24R$. (g) $28R$. (h) $32R$.

Figure 5.2: Spatial development of POD mode number 1 for 0.1% TI.



(a) $4R$. (b) $8R$. (c) $12R$. (d) $16R$.

(e) $20R$. (f) $24R$. (g) $28R$. (h) $32R$.

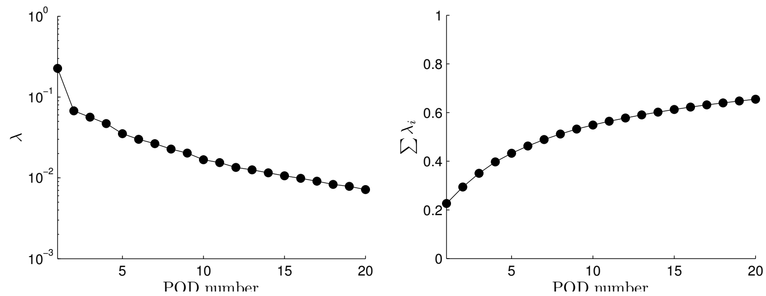
Figure 5.3: Spatial development of POD mode number 1 for 11% TI.

5.3.2 Subtask 4.2

The flow field is simulated for the idealised case of an infinitely long row of wind turbines by applying cyclic boundary conditions in the streamwise direction. The flow simulations are run for $70mins$ real time, so flow inside the wind farm has reached a random stationary process, where the incoming mean wind as experienced by the turbines have stabilised around 0.7 of the initial wind speed equivalent of $15m/s$. The wind turbines are spaced $12R$ apart.

POD is applied to 1119 velocity slices extracted $1R$ upstream the wind turbine, covering a total of $10mins$. Figure 5.4 shows the normalised POD eigenvalues and the cummulated eigenvalues, i.e. the amount of turbulent kinetic energy captured by the POD modes.

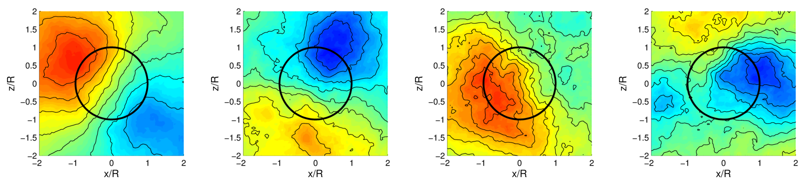
Figure 5.5 shows the spatial POD modes 1,2,3, and 4 for the streamwise velocity component. The



(a) (b)

Figure 5.4: POD eigenvalues. (a) Sorted POD eigenvalues. (b) Cummulated POD eigenvalues.

first modes of U show clear dipole structures with extrema located outside the rotor plane. This looks very similar to the spatial structures portraited in Figure 5.3.



(a) Mode 1 U. (b) Mode 2 U. (c) Mode 3 U. (d) Mode 4 U.

Figure 5.5: Spatial POD modes 1-4 for U. Circle marks the rotor area.

Table 5.1 gives an overview of the optimised Reduced Order Model for the top four POD modes. The dominant frequencies for each POD mode is given along with the linear least squares optimised coefficients which gives rise to a coefficient of determination, i.e. the goodness of fit between the flow field reconstructed using POD and with the Reduced Order Model. Finally, the fraction of turbulent kinetic energy captured by the POD reconstruction is given.

Using only five distinct frequencies, it is possible to reconstruct 22% of the total turbulent kinetic energy with $R^2 = 77\%$, where the most dominant frequency $f = 0.00832Hz$ accounts for 48% of the total energy in POD mode 1. The table gives the top nine frequencies, which reconstructs 40% of the turbulent kinetic energy contained by these large scale structures with $R^2 = 0.60$.

It is noteworthy that several of the dominant frequencies for the individual POD modes are the same, i.e. $f = 0.00832Hz$ and $f = 0.01665Hz$. This indicates that the large scale dynamics of the flow originates from combining these spatial dynamics using similar frequencies.

Figure 5.6 compares the streamwise velocity from CFD(black), POD(red) and the Reduced Order Model(blue) reconstruction at the rotor centerline. The fast and at times large fluctuations are not captured by neither the POD nor the Reduced Order Model reconstructions, as expected. However, both clearly capture the low frequent dynamics. This is also shown in Figure 5.7, which shows snapshots in time of the streamwise velocity as given by CFD and the Reduced Order Model. The wake is very dynamic and although the Reduced Order Model only includes a limited number of frequencies and POD modes, it generally captures both the location of the wake deficit and the distortion of the wake, hence the large scale dynamics of the system.

Table 5.1: POD mode (k), frequency number (m), frequencies ($f_{k,m}$), linear Least Squares fitted coefficients ($\beta_{k,m}$), coefficient of determination between the reconstructed flow using POD and the Reduced Order Model(R^2), and energy fraction of POD modes ($\sum_{i=1}^{k} \lambda_i$).

k	m	$f_{k,m}[Hz]$	$\beta^{(1)}_{k,m}$	$\beta^{(2)}_{k,m}$	R^2	$\sum_{i=1}^{k} \lambda_i$
1	1	0.00832	-5.39	3.25	0.48	0.226
1	2	0.00999	0.19	3.39	0.62	0.226
1	3	0.01665	1.89	1.33	0.68	0.226
1	4	0.02498	-1.86	-0.84	0.73	0.226
1	5	0.00666	1.66	0.78	0.77	0.226
2	1	0.01665	-2.21	1.00	0.65	0.294
2	2	0.00999	-1.84	1.51	0.70	0.294
3	1	0.00832	-0.24	2.93	0.65	0.350
4	1	0.01665	1.85	-0.09	0.60	0.397

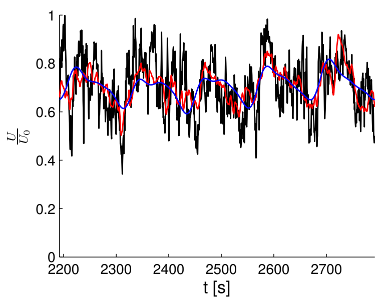


Figure 5.6: Comparison of the normalised streamwise velocity at the rotor centerline for CFD results(black), POD(red) and Reduced Order Model(blue) reconstructed using 9 frequencies.

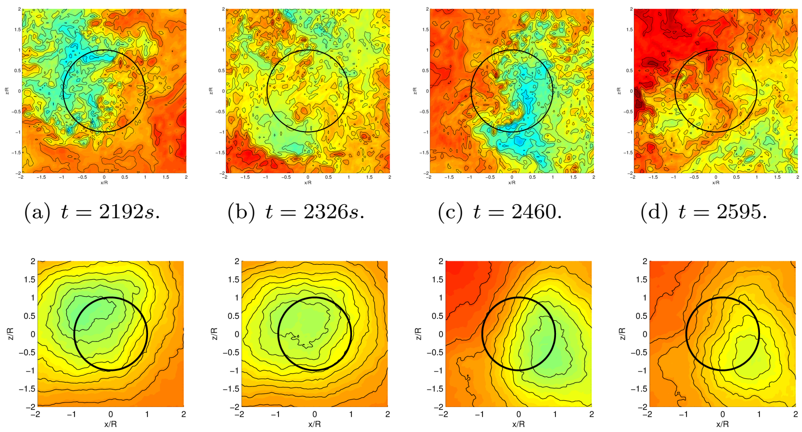
5.4 Discussion

The reduced order model needs to be verified by further investigation of the number of spatial POD modes and frequencies needed to capture the dynamics satisfactory. This verification will be done using the reconstructed flow field as input to Flex5 without using full CFD simulations. The reconstruction of the flow could potentially be combined with high frequency turbulence to account for the energy deficit and the more extreme fluctuations.

5.5 Conclusion - subtask 4

The wake development behind a wind turbine is investigated which forms the baseline for understanding the wake development and behaviour in both near and far wake region.

A Reduced Order Model is constructed from a Proper Orthogonal Decomposition of an idealised flow case with in an infinitely long row of wind turbines. The Reduced Order Model consist of combining the spatial structures with a truncated representation of the temporal eigenfunctions by choosing the dominant frequencies for each POD mode. The Reduced Order Model is shown to reconstruct the flow in a physically correct manner by capturing the low frequency dynamics using



(a) $t = 2192s$. (b) $t = 2326s$. (c) $t = 2460$. (d) $t = 2595$.

(e) $t = 2192s$. (f) $t = 2326s$. (g) $t = 2460$. (h) $t = 2595$.

Figure 5.7: Spatial comparison of U from CFD results (top row) and Reduced Order Model (bottom row) at different time steps. Circle marks the rotor area.

only nine frequencies distributed on the first four POD modes.

5.6 Future work

Future work will focus on including the effects of the atmospheric boundary layer to capture additional complexity. The reduced order model will be constructed for a range of scenarios, i.e. various spacings between the wind turbines, various initial inflow conditions, in order to parameterise the model for more generality.

Chapter 6

Subtask 5. IceWake

6.1 Aim of subtask 5

The onshore wind energy development is gradually increasing especially in Nordic countries with the areas where the cold climate conditions and icing bring technical difficulties and cause power production losses. Power losses due to icing suffer from large uncertainties due to the challenge for predicting ice accretion on the wind turbine blades. This PhD project aims to develop a better understanding of how moderate icing affects the total production of wind farms and to further link meso- and micro-scale simulation methods. Two Norwegian companies are involve in this task with activities of meso-scale modeling and commercial software development.

A main objective of the meso-scale study is to generate knowledge that can improve the description of the atmospheric boundary layer dynamics and possibly generate results from meso-scale modeling that can be used as boundary conditions for micro-scale simulations.

6.2 Subtask 5.1 Generation of aerodynamic coefficients for iced airfoils

To be able to run full scale LES simulations based on the actuator line and actuator disc method, aerodynamic coefficients corresponding to iced conditions are needed. Today, the knowledge in this area is limited. LES simulations are performed to generate modified blade shapes due to icing, i.e., when the ice attaches to the blade.

LES simulations are performed where water droplets are released and transported upstream the airfoil. This is modeled using the immersed boundary method with a Lagrangian particle tracking solver for the transport of water droplets in the computational domain. Different cases are performed to represent icing levels due to the atmospheric conditions. This is to mimic different atmospheric and icing conditions by changing the parameters; amount of droplets, droplet size, liquid water content and wind speed. The result will give a database of new geometric shapes of airfoils due to different icing conditions. When new blade geometries are derived for different atmospheric conditions resulting in icing, the corresponding aerodynamic coefficients can be derived using XFOIL, QUICK or 2D CFD simulations depending on the complexity of the shapes of the iced airfoils derived. This database will then be used to quantify relations between different icing levels and lift and drag coefficients needed to perform LES simulations of farms with moderate icing.

A collaboration with Laszlo Fuchs from KTH and Robert Szasz, from Lund University has started regarding the ice accretion simulations.

6.3 Subtask 5.2, Large-eddy simulations to predict icing effect on wind farm energy production

In this task, CFD simulations are performed for different icing conditions on chosen airfoils. The application is to predict the ice accretion on a full wind turbine blade and investigate the icing effect on wind farm energy production.

6.4 Subtask 5.3 Meso-scale Modelling

The IceWind research project seeks to address some of the barriers to large-scale integration of wind energy in the Nordic countries. Through improved forecasts and acquiring an overview of icing conditions, wind farms will have a better chance at contributing to a higher share of renewable energy in the Nordic countries. In a parallel subtask in the ICEWIND project, the icing calculations have been focused on application of the mesoscale model calculations to Sweden and a preliminary Ice map for Sweden has been published. The ice model and the model for energy losses due to the icing have been validated. An IceWind report on the icing calculations is under development and will be finished in the second half of 2012.

In this subtask a collaboration between the University of Gotland and Kjeller Vindtekknik (KVT) is established on the wake calculations. At KVT work is under progress setting up the mesoscale model WRF for wake calculations. A clarification with respect to wind farm experimental data for wake studies at Lillgrund is still needed from Vattenfall before validation of model experiments can be carried out. In WP4 KVT has put resources into obtaining real time energy production data from the Norwegian utility companies. KVT has got permission to use the wind energy data sets within IceWind under the requirements that the energy production data cannot be revealed and that the data are not distributed to any third party outside KVT. KVT has worked with VVT and DTU on the variability of the energy production in the Nordic area. A paper by Hannele Holltinen on this issue has been presented at the 11th Wind Integration Workshop in Lisboa November 2012.

Large Eddy Simulation (LES) CFD models such as EllipSys3D, using actuator disc methods to represent the energy extraction from wind turbines, have shown promising results in reproducing the actual wind energy production from wind farms. There are however issues related to the how well the inflow conditions, in terms of vertical wind profile and atmospheric turbulent eddies, are described. It is well known that the background atmospheric turbulence has a significant impact on the wind turbine wakes. In particular it is observed that for unstable stratification, where the high levels of background turbulence act as an efficient mixer of momentum, the wind turbine wakes recovers faster than for neutral stratification. The opposite is observed for stable stratification. Therefore it is important to include these effects in the models that describe the flow. One way to achieve this is to use input from a numerical weather prediction model both in terms of inflow vertical wind profile, but also to characterize the stability regime at a given time.

The Weather Research and Forecast (WRF) model can be used in mesoscale mode, where the vertical exchange of for instance momentum is parameterized. A typical horizontal resolution is in the order of 1 km. It can also be used in micro-scale mode, commonly referred to as WRF-LES. At typical horizontal resolution is in the order of 10 m - 100 m. In the former case one cannot expect to achieve knowledge on small scale eddies. In addition the vertical profile will be determined by similarity theory. One advantage, however, is that the similarity profile is determined by the heat exchange from the ground. In other words it is possible to use the mesoscale data to determine/classify the atmospheric stability conditions. KVT is at the moment setting up the WRF mesoscale model for the Lillgrund wind farm.

Recently WRF-LES has been subject to increasing interest, especially from the research community, due to increased available computational resources. Most simulations have been performed on idealized cases, and comparisons with measurements are scarce, hence validation of quantities such as vertical wind profile and turbulence statistics still remains to be done. Still with the WRF-LES model one has the possibility of obtaining realistic values for both of these, and to account for different atmospheric stability regimes. There are plans at KVT to set up the model for the Lillgrund wind farm.

An actuator disc wake model is implemented in WRF. This provides an opportunity to study the large scale effects from the wind farm, and thereby how the wind farm affects the local meteorology. The Lillgrund wind farm also presents an opportunity to compare the results of the WRF wake modeling with the more advanced EllipSys3D model.

6.5 Subtask 5.4 Commercial software development

Traditionally simplified linear methods have been used to determine the wind fields within the wind sector. Recently CFD, which is a non-linear method, has been recognized as a more accurate method for wind field characterization. The fundamental behavior of fluid flow is described by the Navier-Stokes equations. The Navier-Stokes equations are non-linear partial differential equations that are known to be unstable and difficult to solve. Therefore simplified methods, where the troublesome non-linear terms have been linearized have become popular. However, the severe penalty is the reduced accuracy. Non-linear simulations requires more computer resources than linear simulations, but with today's computer resources even ordinary PCs can perform CFD simulations. CFD has proven to be a useful method within many industries where it has become the standard method for flow characterization. Also within the wind sector there is a trend moving from linear to non-linear methods.

WindSim AS develops the software WindSim, a CFD based simulator for prediction of local wind fields. WindSim is used within the wind energy sector to maximize the energy production and minimize the loads on the turbines. Due to its CFD basis, WindSim is capable of handling situations with complex terrain, vegetation and atmospheric conditions. Due to the fundamental approach of the underlying CFD method, innovative wake modeling can be set forth. WindSim have established a wake model based on the actuator disk concept. In particular with the upcoming plans for large offshore wind farms the wind industry has been looking for better models for the wake-wake interaction.

6.5.1 Wake modelling

Wake effects have traditionally been addressed with so called analytical wake deficit laws; e.g. the models set forth by Jensen, Larsen, Ainslie, etc. These are all single wake models, as such they don't take into account the wake-wake interaction, nor do they take into account terrain effects or thermal effects.

When using single wake models the wake-wake interaction is generally handled by various sorts of summation of the wake effects from each turbine. These models are empirical in its nature and can't be expected to reproduce the wake-wake interactions for arbitrary layouts. In large offshore wind farms the wake-wake interaction is important. In addition the lower level of ambient turbulence offshore increases the extension of the wakes. Finally the thermal effects offshore might differ from typical onshore situations. All these effects are not addressed properly by the analytical wake models. As a response, we see these days a large number of research initiatives within fundamental wake modelling.

One fundamental approach is the Actuator Disc Concept, where a disc will mimic the resistive force of a real turbine, this will generate a wake that will interact with terrain, other wakes and thermal effects. The rotor of a wind turbine is modeled by an actuator disc providing a resistive force which is calculated from the thrust coefficient CT. The axial thrust can be distributed over the swept area in various ways e.g. by a uniform, parabolic or a polynomial distribution. We believe that the inclusion of wake calculations within the CFD calculations can lead to a better level of estimations compared to any analytical wake model.

Both analytical wake deficit laws and the actuator disc concept have been implemented in WindSim. The actuator disc concept has been under development over several years, starting with calibration against the analytical models and experimental data for a single wake. Today validations against real production data from large offshore wind farms have also been done in collaboration within the Nordic Consortium. The implemented methods has also been compared with state of the art research simulations.

Today, actuator disc methods used in commercial softwares, such as WindSim, do not use the full implementation of the use of aerofoil data due to the complexity and need of computational power. However, it is very important to map the limitations in this approximation and that is important work that is ongoing in the Nordic Consortium.

6.6 Results

6.6.1 Subtask 5.2 Large-eddy simulations to predict icing effect on wind farm energy production

First wind farm simulations have been performed to investigate how icing affects the wind farm energy production during reduced energy outage due to moderate icing. To mimic the icing effect on the blades, different pitching angles were used in the simulations. LES of a farm with 16 turbines was performed with different pitch angles. Results show here illustrates a wind direction that is aligned with the turbine rows. To represent different level of ice +2, +4 and -2 pitch angles degrees where applied to all turbines. The production results of all cases were compared with the zero pitch angle case as a reference to investigate the production loss due to this modification. The performed work is step one in investigations of how equally derated turbines with the same level of icing, affect the total farm production. The investigation will further on be based on lift and drag coefficients derived from work package 5.1., i.e., a more realistic model for lift and drag coefficients.

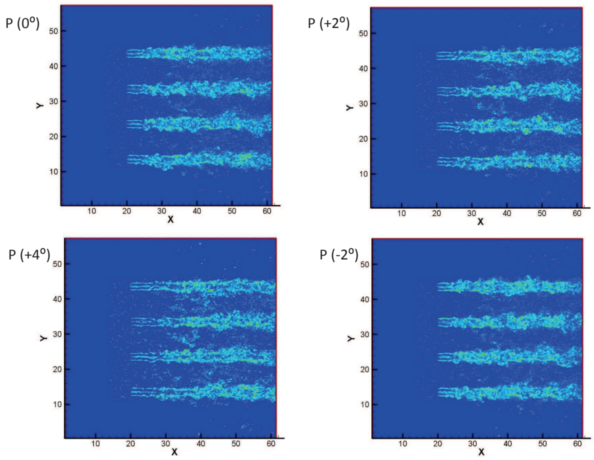


Figure 6.1: Vorticity figures of different pitch angle cases

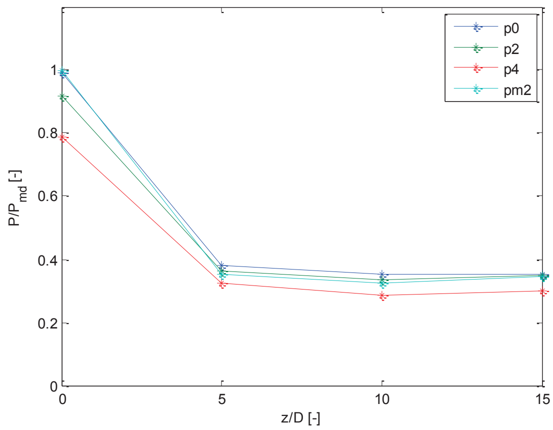


Figure 6.2: Production results of full wake sector. The production results are normalized with reference case with 0 pitch angle. The different colors indicate different cases. The y-axis shows the normalized production. The x-axis shows the downstream position in rotor diameters.

Figure 6.1 illustrates the vorticity of the wind farm containing 16 turbines with different pitch settings. Figure 6.2 shows the corresponding calculated production. and how it varies with the pitch settings.

6.6.2 Subtask 5.3 Meso-scale Modelling

In 2009 KVT created onshore and offshore wind atlases including a 1 km run of WRF for Norway for one selected year. An icing atlas for Norway was also developed. The customer was the Norwegian Water Resources and Energy Directorate (NVE). From 2009 to 2012 KVT participated in the EU funded project NORSEWInD, where the aim was to create offshore wind atlases of the North, Irish and Baltic Seas using a combination of LiDAR measurements, satellite observations, met masts and mesoscale meteorological models. KVT was responsible for creating the final atlases for the North and the Irish Seas using the WRF model. Validation of long-term adjustment methods was also included in the program. In 2011 KVT developed wind and icing atlases for Sweden. In 2012 KVT created 60 years time-series of aggregated wind power production and solar photovoltaic production based on WRF for Northern Europe on behalf of Statnett. In 2012 KVT was awarded contract with OWA Carbon Trust on mesoscale modeling development project for offshore wind farm exploitation in the North Sea. In 2012 KVT received funding from Elforsk to develop a state-of-the-art report on long-term correction of wind measurements. Issues such as the consistency of different long-term datasets, and the applicability of different long-term correction methods, are investigated. The final report will be publicly available through Elforsk and KVT's websites on mid-January 2013.

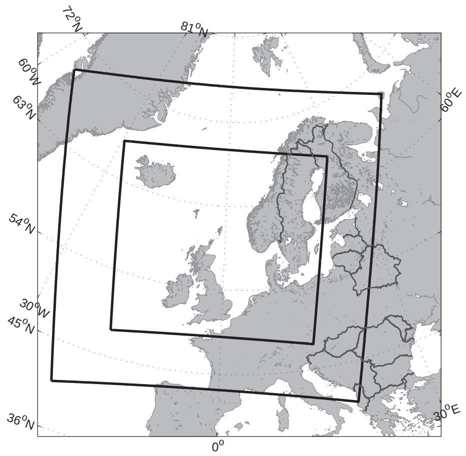


Figure 6.3: Model set up for WRF simulations of Sweden

6.6.3 Subtask 5.4 Commercial software development

The wakes induced by the wind turbines are modeled with the finite-volume code WindSim, based on the solving of the Reynolds Averaged Navier-Stokes (RANS) equations of an Atmospheric Boundary Layer. The RANS equations of an incompressible flow are solved with a multigrid coupled solver (MIGAL); turbulence is closed with the RNG model. The rotor of a wind turbine is modeled by an actuator disc providing a resistive force which is calculated from the thrust coefficient curve of wind turbine. The axial thrust can be distributed over the swept area in three different manners: by a uniform, parabolic or a polynomial distribution.

A wake is therefore generated downstream of each turbine with wake deficit and induced turbulence. When using the actuator disc technique it is also interesting to observe how the wake-wake and wake-terrain interactions are predicted; moreover, also simulations with actuator discs and flows with thermal effects can be carried out.

Chapter 7

Subtask 6. Optimization and control of wind farms

7.1 Aim of subtask 6

During the TOPFARM project [11] one of the main goals was to try to extend the state of the art approach to wind turbine system analysis (i.e. aeroelastic simulation with turbulent wind input), into the wind farm domain. Since the ability to model wind farms using CFD has evolved significantly over the past decade, this approach has naturally drawn a lot of focus. One important limitation, however, is that detailed CFD modeling of wind farms requires large computational resources (multi-node clusters with several cores per node). Today only universities, some research institutes, and the largest wind turbine manufacturers have access to such computer systems, while consultants and smaller R&D units usually work with computers of *workstation* type. Thus a faster and more approximative way to treat the *dynamic windfram* problem would also be very valuable.

In order to facilitate reasonably fast computations, the flow modeling has to be based on some form of Fourier synthesis for the different scales of turbulence. Relying heavily on the *passive tracer* assumption for the wake transport, a basic flow chart for a dynamic wind farm analysis can be outlined as in Figure 7.1.

7.2 Task description

The task has focused on improving the models and procedures in some of the ”boxes” of Figure 7.1. The final goal is a full dynamic wind farm model where each wind turbine is represented by an individual aeroelstic simulation, and where interactions between the turbines is modeled by tracking wakes in the low frequency (large scale) turbulent flow. In the top layer, a general wind farm control system decides the *rating* for every turbine. In contrast with the CFD modeling efforts described in previous chapters of this report, the simulation times are expected to be kept down to the order minutes-to-hours.

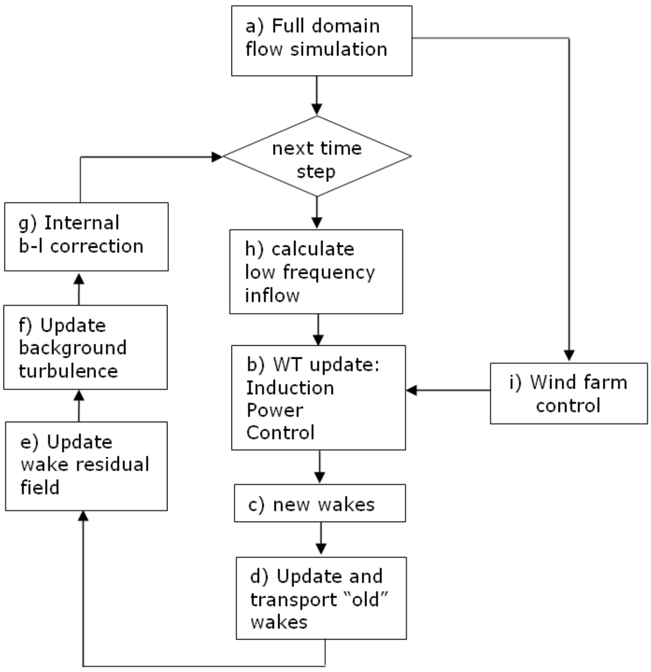


Figure 7.1: Outline of the dynamic wind farm simulation procedure (without a CFD description of the flow)

7.2.1 Subtask 6.1 Wind farm control

Any control concept used for wind turbines or wind farms, has to be based on on a detailed understanding of rotor aerodynamics. If it can be assumed that the rotor blades are rigid, then most relations of interest can be reduced to depend on blade pitch angle, and tip speed ratio. However, if the aerodynamic relations depend significantly on blade deformations then a considerably more complicated analysis is required. In Task 6 a quasi-steady geometrically nonlinear rotor model was developed in order to accurately assess the aerodynamic characteristics of modern flexible wind turbine rotors (where the blade torsion adds several degrees to the effective angle of attack). It should here be stressed that the concept Cp-λ scaling should be used with great care as turbines are growing in size, and advanced technology is adopted in the design. Figure 7.2 shows examples of rotor thrust force along lines of equal power (as function of pitch angle and tip-speed ratio). It should be noted that near the optimal settings, the thrust force varies just slightly with rotational speed. Thus when the derated turbine operate in partial wake, it should be considered to run above optimal speed in order to reduce the risk for deep stall. Using the demonstrated relations, rotor thrust may be traded against power production, in order to try improve the situation for downstream turbines.

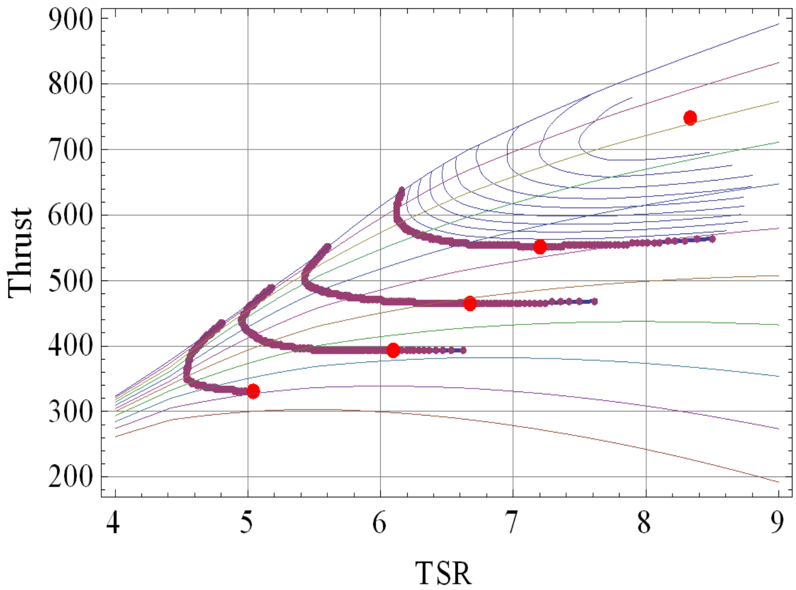


Figure 7.2: The lines of constant rating (i.e. for 12 m/s) transformed to rotor thrust. The lines of constant power represent 100%, 90%, 80%, 70%, and 60% of full rating respectively (IEA/UPWIND 5MW benchmark turbine). The combinations of pitch angle and tip-speed-ratio representing minimal thrust are marked with red dots.

The data behind the purple lines in Figure 7.2 is then packed as multidimensional tables (here denoted as "rating tables"), for efficient access in various phases of the controller design process. In the present study, the rating tables were used to provide thrust and power data for a robust wind farm control algorithm. An iterative scheme was implemented where different types power ratios are evaluated in every step. The most important step is here the evaluation of the relative difference in power production within all interacting turbine pairs (where the distance of separation is less than 10 D). If the difference in power production exceeds a predefined value, then the upstream turbine is derated. Finally, if the iteration leads to an acceptable decrease in total farm production, then all turbines are uprated. The basic algorithm may then be formulated as follows:

```
Repeat until P_Farm < (1-λ)P_Unmanaged
 i=i+1
 Calculate power (and thrust) for all turbines
 for all pairs
  if P_A > (1+α)P_B then derate A by δ(i)
 Next pair
END*
```

This *power balance* approach to wind farm control is illustrated in Figure 7.3. Here a second balance is also introduced, where the production of the *unmanaged farm* (no farm control) has to be estimated through the control systems of the individual turbines. An important feature of the proposed concept, is the possibility to derate the entire wind farm in a structured way, in case there is such a demand from the grid.

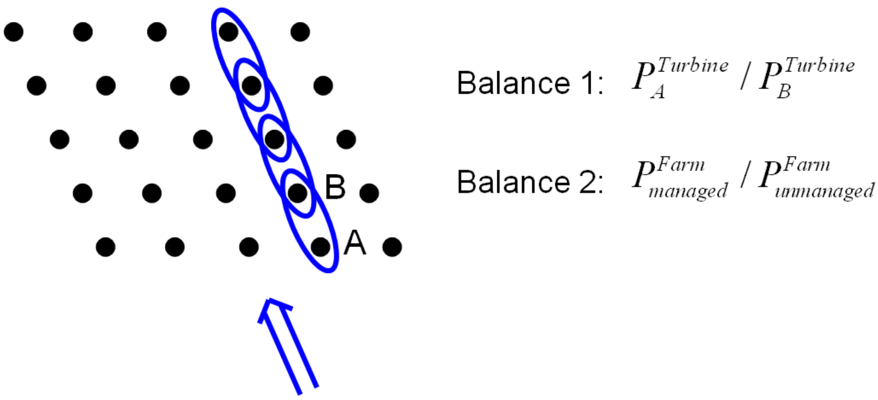


Figure 7.3: Schematic picture showing the *power balance* principle.

An example of a *power balance* iteration is presented in Figure 7.4 (10 m/s , 6D spacing , one row of 5 MW turbines). The differences in rotor thrust and power production are here efficiently reduced, while the total farm output is slightly increased. A description of the wind farm models used here, and a discussion a other simple wind farm control strategies, can be found in [3].

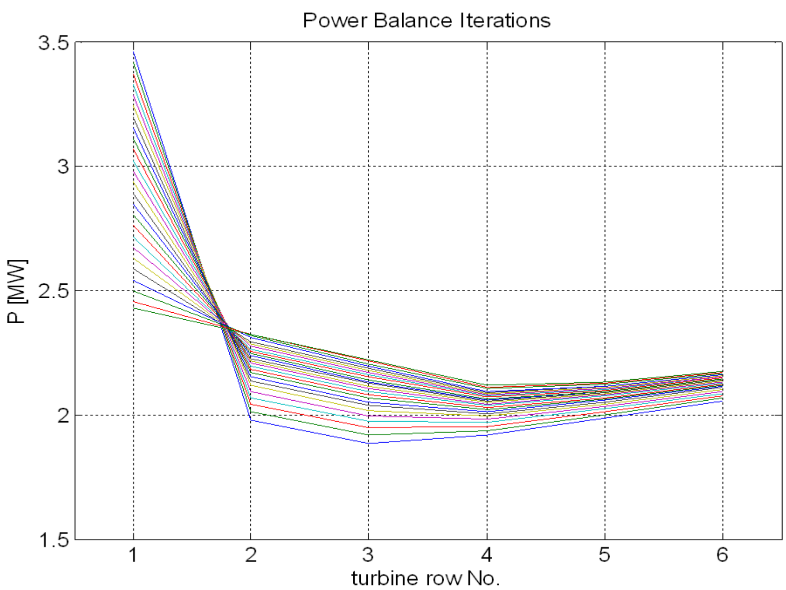


Figure 7.4: Power production for 6 turbines in a single row of a wind farm.
Each line represent an iteration in the power balance scheme

7.2.2 Subtask 6.2 Wind farm domain flow

There have been some recent efforts aiming to implement parts of a simulation procedure similar to the one outlined in Figure 7.1. In some cases the modeling of large scale turbulent variations of wind speed and wind direction inside the farm, have been based on the assumption that Taylors's hypothesis is valid over distances greater than 5 to 10 turbine diameters. This approximation is usually straight forward when the separations of interest are mainly lateral or vertical, but when the application is wake transport in a mainly longitudinal direction the strong correlation downstream is unrealistic. A simplified 2D study during the early stages of the current project clearly revealed that this is a bad approximation. Large scale turbulence was simulated in the x-y plane over an area covering two interacting turbines. A *wake* was emitted in the flow as a spatial filter over one rotor diameter. This *wake* was the assume to be transported down the flow with the local (filtered) wind vector. The lateral position of the wake center was registered as function of time. The same procedure was then repeated, now removing the time dimension and instead *traversing* the frozen turbulence in the wind direction with the average wind speed. The resulting time series of lateral wake center motion are presented in Figure 7.5

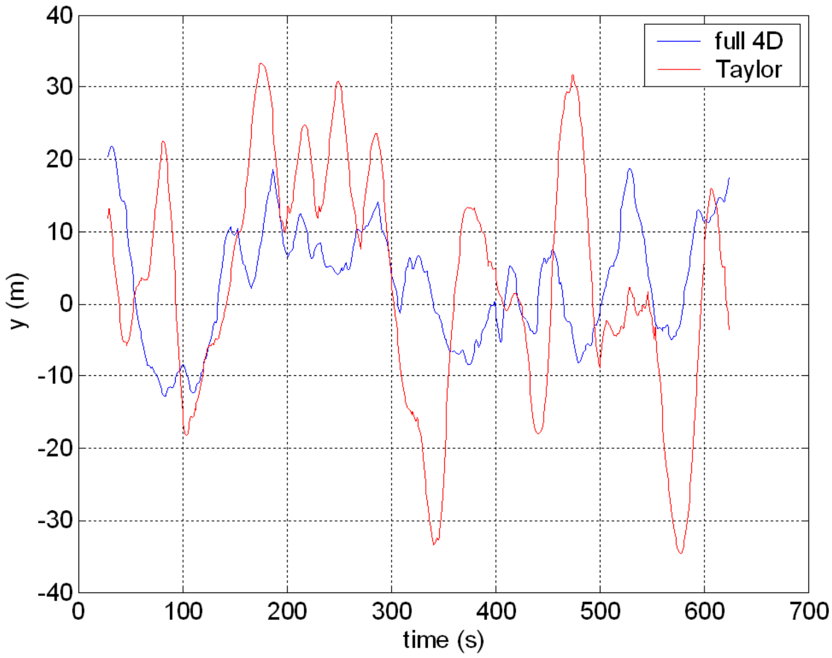


Figure 7.5: Example of wake center lateral movement relative to the hub of the downstream turbine (two interacting 5 MW turbines separated 5 diameters).

The conclusion from the interpretation of these results is that an additional dimension has to be added to the domain flow simulations, resulting in a dramatic increase in computation time and requirements for data storage. In order to deal with this situation a new method was developed, where the components of a local wind vector is found as the sum contributions from different frequency regions. For the lowest frequencies a coarse grid is used, and for the following frequency ranges, periodicity can be assumed in both time and space since the corresponding length/time scales are short. These shorter/smaller blocks can then be "reused" in time and space since the high energy contribution from the lowest frequency will cancel out the periodicity in the final result. The cost for the short simulation time and the efficient storage is some additional access time, since the components of a local wind vector are retrieved as the sum of interpolated values from different sources.

Figure 7.6 shows an example where the large scale turbulence over a 6x6 km area around the Lillgrund wind farm has been simulated. In addition to what is normally needed for simulation of rotor plane turbulence, descriptions of correlation (coherence) for longitudinal separation is required.

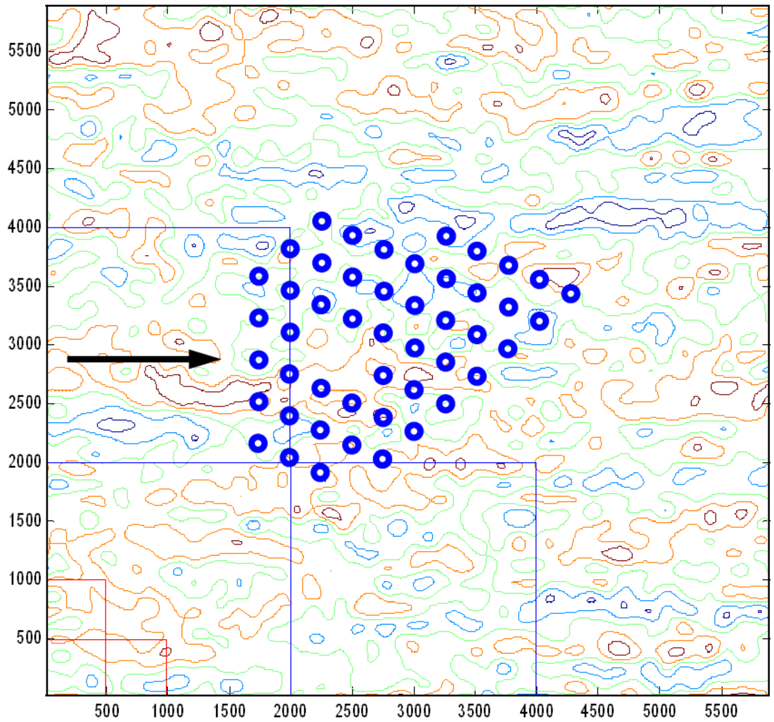


Figure 7.6: Snap-shot (Iso-lines) of hub-height longitudinal wind speed over a 6x6 km area around the Lillgrund wind farm. Blue and red blocks indicate higher frequency contributions (periodic in time and space)

7.2.3 Subtask 6.3 Engineering wind farm models

Many wind turbine wake models have been proposed over the years, of which about five of them often are selected for comparative studies and validation against wind farm production measurements. An ideal wake model for use with the *dynamic wind farm* concept outlined in Figure 7.1, should be a) computationally efficient, b) accurate in the *near wake* as well as in the *far wake* and c) based on some fundamental concept within the field of fluid physics. The latter condition since this makes the calibration of unknown parameters more meaningful. The most popular wake models available in commercial win farm analysis software are named by their respective creators: Jensen, Ainslie, and Larsen.

The Jensen model are based on very simple momentum balance equations, and the wake shape is cylindrical (on/off step). When calculating loads on a wind turbine rotor operating in a wake, the results are more sensitive to the wake shape than when performing production analysis. This makes the Jensen model unattractive in the present context.

The Ainslie model (or *Eddy Viscosity* model) is based on the*thin shear layer* form of the Navier-Stokes equations, and can be fed with an arbitrary description of the longitudinal velocity in the near wake. A solution (longitudinal and radial velocity) can then be obtained at any position downstream, by solving two differential equations with a standard finite difference method. This method is known to give good results, but the computational costs are significantly greater than for the Jensen or Larsen models. Moreover, the sub models for viscosity distribution in the wake usually have several unknown parameters that have to be calibrated against results from higher order methods or advanced measurements.

The Larsen model, which was used for the analyses within Subtask 6.1, is based on an analytical solution of Prandtl's boundary layer equations. It is computationally efficient and provides a smooth and realistic shape in the far field. Several studies have though revealed that the Larsen model leads to over-prediction of production in case of narrow turbine spacing. I contradiction with results e.g. ACL simulations or detailed wake measurements, the Larsen model gives a bell type shape already for very short transport distances.

A variant of the Larsen model is therefore here proposed, where the near field is described by using the distribution of axial induction at the rotor plane, and then applying a pressure expansion according to:

$$r_{w,i+1} = \sqrt{\frac{1-a_i}{1-2a_i}(r_{t,i+1}^2 - r_{t,i}^2) + r_{w,i}^2}$$

where t denotes rotor plane, w denotes near wake (after expansion), and i is a counter for the radial position. This approach is a common choice when assigning boundary conditions for eddy viscosity calculations. The expanded induction is then used to define the wake at 2 diameters from the rotor plane, and up to a chosen distance the wake field is then found by interpolation with the Larsen solution. Results from this combined model appears to be similar to results from eddy viscosity calculations, and the number of parameters that needs to be calibrated are around 2 to 3. This new model will be validated against measurements from the Lillgrund wind farm. A comparison between the Larsen model and the combined model is shown in figure 7.7

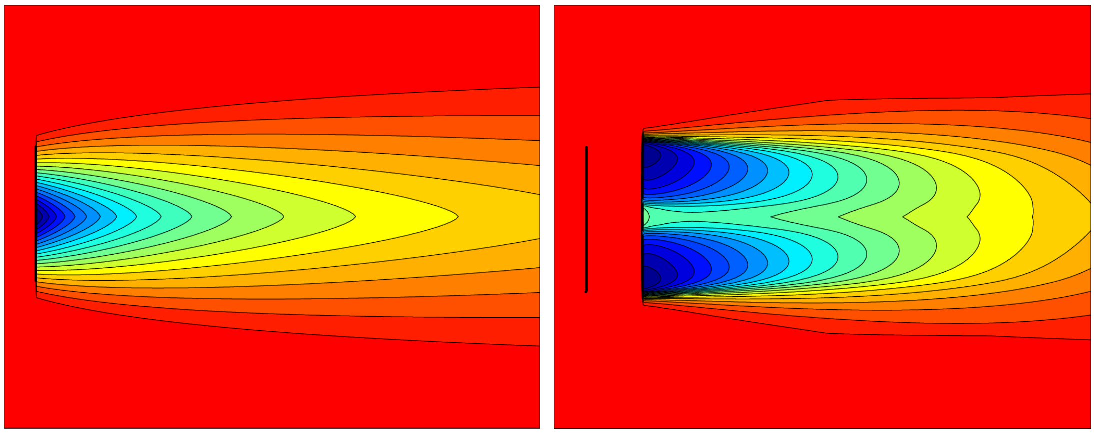


Figure 7.7: Iso plots of longitudinal wind speed in the wake for Larsen wake model (left), and the proposed model (right) . Note that in the right figure, the wake is undefined for x less than 2 diameters downstream.

Chapter 8

Subtask 7. FarmFarm

8.1 Aim of subtask 7

More and larger wind farms are planned offshore. The most suitable sites for offshore wind farms are limited by, for example, a certain range of water depth and distance from shore. Especially in countries with high goals for wind energy integration combined with short coast line this will lead to many wind farms that will be build in the vicinity to other wind farms. With the coming development deeper knowledge will be needed to ensure better production and load estimations, especially when other wind farms are close and will interact with each other. This interaction between farms is called Farm-Farm interaction.

The overall aim of the project is to study wakes behind whole wind farms using numerical methods. The goal is to reduce the uncertainties in production estimations for offshore projects where wind farms, sited relatively close to each other, interact. This could also result in recommendations how large wind farms should be placed relative other wind farms. The project will combine established numerical methods with large scale parallelized simulations (MPI) on clusters.

8.2 Subtask description

This subtask is divided into four parts as presented below:

8.2.1 Subtask 7.1 - Literature study and data collection

In this subtask available wind farms with sufficient data for further studies are searched for. A part of that is also to investigate available studies of wakes in large offshore wind farms.

Existing offshore wind farms are studied to find wind farms standing close to each other. The survey also studies what type of data that are available considering energy production and wind measurements.

The survey is used to find suitable wind farms for farm to farm interaction studies. First the study objects ideally have two wind farms with different commission dates to be able to study the production with and without farm wakes. Secondly, available long time measurement series in a number of directions and in a number of distances from the farm are needed to verify the result of the simulations of the wind farm wake.

Some of the suitable wind farms with accessible data are used for further filtering and used as verification for the wake simulations. The outcome of the task is better knowledge of available data for farm to farm wake studies.

8.2.2 Subtask 7.2 - Needed grid resolution for simulations

The subtask studies the needed calculation resourses using EllipSys3D simulations employing the ACD method for studies of wakes from large wind farms. Large eddy simulations are performed on clusters with many cores using MPI simulations. The aim is primarily to study how many nodes one need to get convergence in the simulation for later studies.

A first test case is set up, with periodic boundary condition for the width of the domain, to simulate the wake up to 5 farm distances behind. (The periodic boundary layer assumes an infinitely wide wind farm.) Simulations are performed to study which grid size that is needed in different places of the domain and how many total nodes that are needed to get convergence in the simulation.

The test case is analyzed regarding how many nodes that are needed for a full scale simulation (with a finite width of the wind farm and taking the wake expansion into account) and what this corresponds to in terms of needed computer resourses using ElipSys3D for LES using the ACD method.

The outcome of the task is knowledge of needed computing recourses for full scale simulations of farm wakes.

8.2.3 Subtask 7.3 - Validation with measurements

The task compares the simulation results for the wakes performed with periodic boundary conditions for a wind farm with the measurement data that is valid for the wind farm. The comparison gives knowledge about how well the model can simulate the conditions for a large wind farm including the farm wake and if any other parameters need to be included in the model, like Meso scale effects.

The outcome of the task is better knowledge about how well the simulation will model the wake behind the wind farm and a better idea of needed modifications in the model to better describe the actual wake.

8.2.4 Subtask 7.4 - Full scale simulations

The task includes a full scale simulation of farm wakes considering, with future knowledge, wind veer, atmospheric stability or other significant parameters. Farm to farm interaction will also be studied.

8.3 Results

A study of available studies and data for farm to farm studies has been performed. Horns Rev has been chosen as a first simulation case for which simulations with periodic boundary condition has been performed and compared to measurements. The results from these studies are here presented divided into the subtasks.

8.3.1 Subtask 7.1 - Literature study and data collection

A paper about available wind farms with suitable data for studies of farm to farm interactions was presented at the 8th EAWE PhD Seminar on Wind Energy in Europe [5].

The paper describes that more knowledge can be gained from simulations of long distance wakes. Some different models used for simulations of Farm-Farm interactions have been mentioned in earlier studies. The models mentioned can be divided into self similar and meso-scale models. The simulation models differ in which parameters are neglected and how the wind farms are included. While the far wake models better model the forces from the wind turbines, the mesoscale models better model the meteorological parameters. Regarding flow field models, different CFD solutions of RANS simulations are considered in earlier studies. LES have also been mentioned but were earlier disregarded due to needed computational recourses. LES studies have later been done of the wakes inside large wind farms and could also with growing computational resourses be extended to also cover the farm wake.

Knowledge can also be gained from measurements either directly by analyzing the measurement data or as a source for validation for simulation models. Measurements can be for a point or volume in a number of vertical positions from measurements in met tower or from ground using LIDAR and SODAR. Alternatively measurements can be done horizontally in the wake by satellite data, SAR and horizontal LIDAR. The long distance wakes can be seen on large distances behind wind farms. The order of the recovery length from measurements and simulations are from 6km up to well above 10km mentioned in earlier studies.

In the paper are also results from earlier presented studies and suitable cases for coming studies.

8.3.2 Subtask 7.2 - Needed grid resolution for simulations

Simulation of the test case for the Horns Rev wind farm with periodic boundary condition is performed with a resolution of the grid chosen to around 20 grid points over the rotor [6]. The exact grid resolution is based on an equidistant grid in the span wise direction (x). The total number of blocks is 168 ($1 * 4 * 42$) and each block consists of 64^3 cells giving a grid of totally 44 million mesh points, (Figure 8.1). The resolution is based on earlier experience. [9] The simulation result gives a quasi stable solution after around 20000 time steps, (Figure 8.2). A study on needed number of node points for a simulation case without the periodic conditions is ongoing.

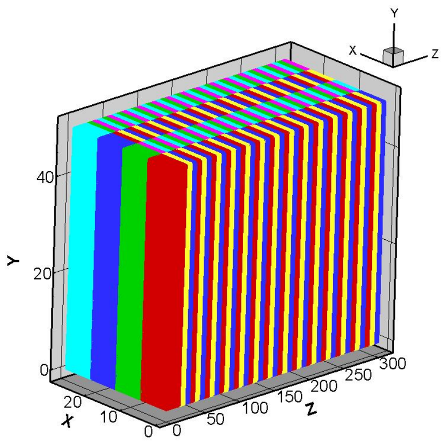


Figure 8.1: The grid consisting of 4 blocks in the span wise, 1 block in the vertical and 42 blocks in the streamwise direction.

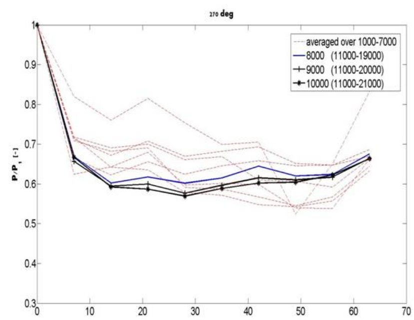


Figure 8.2: Quasi stable solution for normalized power at an averaging time of 10000 time steps, starting from 11000 time steps. The x-axis illustrates the the downstream position normalized to rotor diameters.

8.3.3 Subtask 7.3 - Validation with measurements

A Study of the consistency between the simulation results and the measurement data for the wind farm was performed for the Horns Rev wind farm and presented in [6]. The study of the farm wake was performed using Large Eddy Simulations (LES) of Horns Rev I, an offshore wind farm west of

Denmark. Horns Rev consists of 80 wind turbines in 10 rows (7 degrees (deg) turned from North-South) and 8 columns (West-East), (Figure 8.3). The internal spacing between the turbines in the rows and columns is 7 rotor diameters (D), making the farm about 4 km wide and 5 km long. Two met towers situated 2 km and 6 km respectively behind the farm are available which makes the farm ideal for studies of the wake velocity deficit on longer distances.

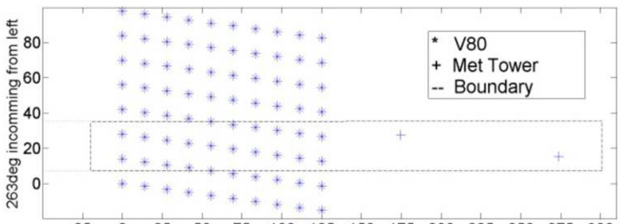


Figure 8.3: The layout of the Horns Rev wind farm turned 7 deg clockwise. The rectangle shows the part covered by the grid which uses periodic boundary conditions.

The simulations were done using an actuator disc (ACD) method. By using periodic boundary condition on the lateral boundaries the simulations can be done using only 20 turbines. This decreases the needed computational resourses. The periodic boundary condition, at the lateral boundaries represents an infinitely wide wind farm, (Figure 8.4).

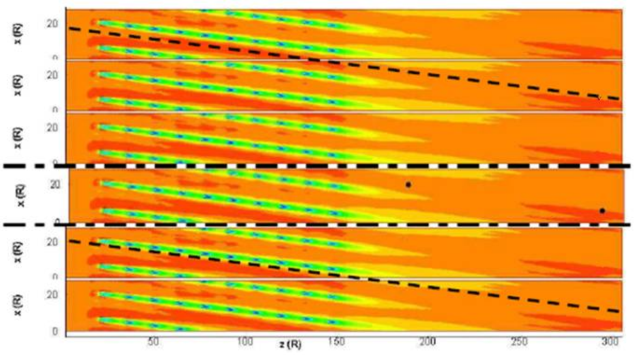


Figure 8.4: The figure illustrates the velocity deficit with an inflow angle of 270 degrees. The black dots shows the two met masts position.

The met tower data shows a clear recovery in the very far wake. The measurements are done with met masts at hub height and filtered to correspond to the simulated cases, (Figure 8.6). For the same cases filtered production data for the wind turbines are also available, (Figure 8.5).

8.3.4 Subtask 7.4 - Full scale simulations

Setting up a case without periodic boundary conditions will give a better knowledge about also the wake expansion. For this also some measurement data is needed, possibly satellite data or lidar data.

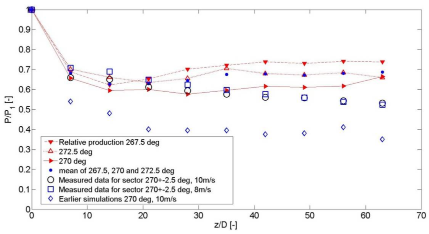


Figure 8.5: The figure illustrates simulated normalized production compared with measured data.

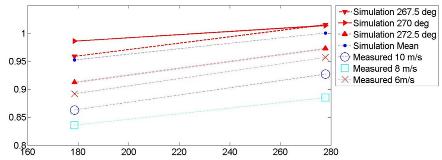


Figure 8.6: The figure shows the measured wind speeds at the two met masts normalized with undisturbed wind.

The simulations is planned to be performed later on in the project.

8.4 Discussion

Simulations of large distance wakes can give knowledge about how wind farms interact with each other. Different types of simulations can be used for simulations of long distance wakes. The LES model used in this project is rather computationally heavy although by modeling the turbine with ACD some computational power is saved for the wake. The wind shear and the turbulence are included in the model by body forces. For long distance wakes it needs to be considered if other meteorological parameter needs to be included as well, for example the atmospheric stability.

8.5 Conclusion

Many plans for offshore wind will result in wind farms being built so close that the farms will interact with each other. Some cases are already built, out of which here Horns Rev is chosen to be studied. LES have earlier not been used for farm-farm studies, but the LES simulation done for Horns Rev shows that LES can be used also for simulation of long distance wakes.

8.6 Future work

The first step is to further verify and examine the sensitivity of different parameters, like grid resolution, turbulence level and airfoil data, in the performed simulations. Wind veer will be included in the simulation as a first step towards considering the Coriolis force in the simulations. When suitable measurement data is available for the whole wake simulations without periodic boundary condition will be performed and verified. Further on a coupling between the used method and meso-scale models will be examined.

Chapter 9

Subtask 8. IEA Wind projects

9.1 Aim of subtask 8

The aim of this task is to study wind turbine and wake aerodynamics. Experimental data, acquired either in a wind tunnel or in the field, are used to validate predictions for different simulation models. The different models are also compared together in this validation process.

9.2 Subtask description

This task is under the auspices of the International Energy Agency (IEA) and contains two subtasks that are described below. Previous described subtasks are included into these IEA activities but for simplicity the activities are describer as a separate subtask.

9.2.1 Subtask 8.1: Wind Task 31, WAKEBENCH: Benchmarking Wind Farm Flow Models (VindForsk III, V-355)

This IEA annex was started in October 2011, with a kick-off meeting held at CENER is Spain. A preliminary kick-off meeting was also held at Gotland University in parallel to the Wind Turbine Wake Conference held in June 2011. The operating agents for this Annex are Javier Sanz Rodrigo from CENER and Pat Moriarty from NREL.

The objective of this task is to define quality-checked procedures for simulating wind and wakes. A forum is provided for industrial, governmental and academic partners to develop such procedures, together with improving models of the atmospheric boundary layer and wind turbine wakes that are used in wind energy[8]. Benchmarking several wind and wake modeling techniques will be used in order to determine the best practices for the use of these models under different conditions, both offshore and onshore, and under complex and flat terrain conditions. Results from the different models will be compared to each other, as well as to experimental data, in an effort to quantify the uncertainty bounds associated to each type of model. The stated objectives of this task are[27]:

- *"To make an inventory of state-of-the-art models for the simulation of wind and wakes for site assessment applications: inputs, model equations, outputs, etc.*

- *To define procedures for the definition of test cases for validation purposes of wind and wake models: requirements on measurement data, filtering processes, metrics, etc.*

- *To identify the most critical aspects of the modeling chain by quantifying the associated uncertainties: boundary conditions, turbulence model, stability, etc.*

- *To define the range of applicability of the models under investigation: site conditions, wind regimes, wind farm size, etc.*

- *To reach consensus on best practice guidelines for the verification and validation of wind and wake models.*"

Many countries are participating in this international research effort, among others, Canada, Denmark, Germany, Greece, Italy, the Netherlands, Japan, Spain, Sweden, Switzerland, United Kingdom, and the United States. Work will focus for the different participating groups on performing benchmarking exercises on validation test cases. A web platform called "WINDBENCH" will be created for the management of the test cases. It will include information regarding the specific benchmark cases, as regards the schedule, necessary data, and standardized procedures defining the test cases. The participants will agree on an evaluation protocol, and a scientific committee will supervise that each case is correctly implemented. Each benchmark case will result in a report. Fig. 9.1 [8] shows a sketch of the WINDBENCH platform. An IEA-Wind best-practice guideline report will consist in the final deliverable of this Task, and will be based upon the guidelines resulting from each benchmark report.

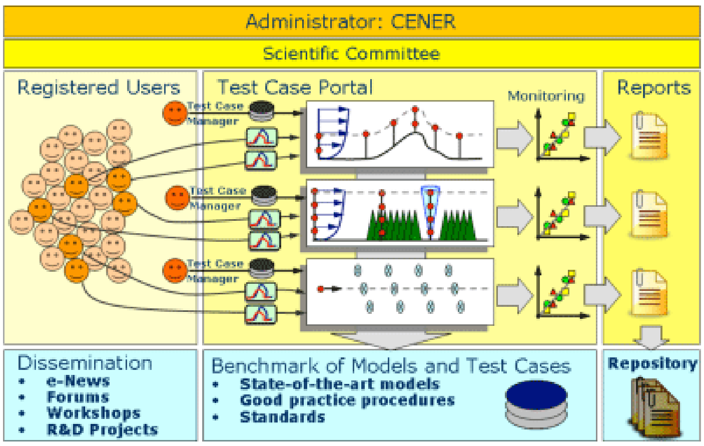


Figure 9.1: Sketch of the WINDBENCH platform to be used to manage the different benchmark cases.

Table 9.1 summarizes the planned benchmarks, called test cases (WG).

It is possible that more tasks are added in the future. The wind energy research group at Gotland University has manifested in September 2011 its interest in participating to WG 6, 7, 8 and 9.

9.2.2 Subtask 8.2: Wind Task 29, Mexnext: Analysis of Wind Tunnel Measurements

This IEA annex is in two phases. The first phase started in 2008 and lasted for three years. The goal of the first phase was to analyze the measurements performed on the MEXICO (Model Rotor

WG1	Flat Terrain
WG2	Hills in Wind Tunnel
WG3	WG3 Hills in Field
WG4	WG4 Forest
WG5	Mountains (complex terrain)
WG6	Wake Theory
WG7	Wakes in Wind Tunnel
WG8	Small wind farms in the field
WG9	Large wind farms

Table 9.1: Benchmark cases in Wakebench Annex

Experiments In Controlled Conditions) model turbine in the DNW wind tunnel, having as an aim to use the experimental data for code validation purposes. This turbine was three-bladed, and had a diameter of 4.5m[34], see Fig. 9.2. Load as well as flow field measurements were performed on this turbine, and 20 participants from 11 countries, among them Gotland University, participated in this research effort that ended in June 2011. From October 2011, a second phase of the Mexnext Annex was approved, and will also allow to put together the research effort of many different research institutes throughout the world in an attempt to better understand wind turbine and wake aerodynamics.

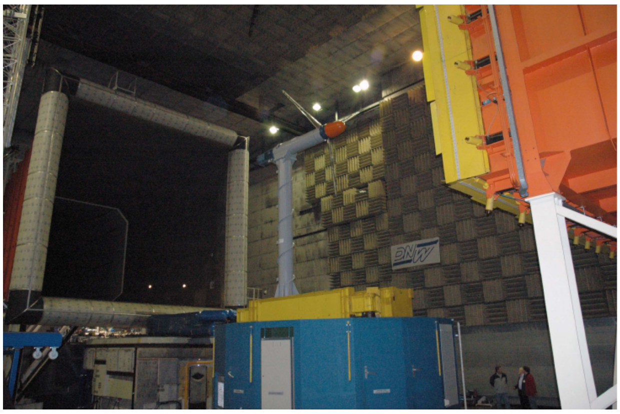


Figure 9.2: Set-up of the Mexico turbine tested in the DNW wind tunnel.

9.3 Results

9.3.1 Subtask 8.1

Simon-Philippe Breton and Ola Eriksson participated to the Wakebench meeting held at NREL in Boulder, Colorado, from the 7th to the 9th of November 2012. The main goals of this meeting were to discuss the contents of a Model Evaluation Protocol and to present results from the initial benchmarks. which was done by the task leaders. The research group at HGO did not participate to the initial benchmarks, but Simon-Philippe Breton presented preliminary results obtained by the HGO research group relatively to taks 9. More specifically, simulations of the Lillgrund and Horns Rev wind farms, located respectively in Sweden and Denmark, have been performed using the EllipSys3D code, which solve the Navier-Stokes equations in their incompressible form using a finite volume approach. In this code, the LES (Large Eddy Simulation) technique is used for modelling turbulence, and the wind turbine rotors are modelled as actuator disks whose loading is determined through the use of tabulated airfoil data by applying the blade-element method. Results related to this work can be found in [6] and [23].

9.3.2 Subtask 8.2

The wind energy research group at Gotland University has participated to the first phase of the Mexnext Annex, which resulted in these publications [24, 25].

A kick-off meeting was held in December in 2011 in Amsterdam to define the orientations of the phase II of the Mexnext Annex, to which Simon-Philippe Breton participated. The wishes of the wind energy research group at Gotland University for this new phase were expressed in this meeting, among other things having to do with performing flow field measurements further in the wake of the turbine, as well as using larger measurement windows so that vortex vibration modes can be studied. At the time it was not sure that new experiments would be performed for this second phase.

It was later decided that a new run of experiments would be performed on the MEXICO rotor for phase II of the Mexnext Annex. This was discussed at a meeting held at NREL in Colorado in November 2012, to which Simon-Philippe Breton and Ola Eriksson from the wind energy research group at Gotland University participated. The wishes of the latter concerning the new set of experiments were once again expressed.

9.4 Discussion and future work

9.4.1 Subtask 8.1

More work will be performed in the future on the different WG, and results will be sent to the task leaders so that comparisons can be done in the benchmarking process. Results shown in in[6] and [23] show that the simulation setup for the Lillgrund and Horns Rev large wind farms is ready to participate to the benchmarking task 9. The same simulations have to be run once more using the same set of input data that will be used by all the participants in the benchmark process, that are found in[4]. Differences from using differents sets of input data will also be investigated. Participation to the other WG will be dependent upon the time available to the research group to perform the different simulation tasks.

The next Wakebench meeting will be held in June 2013 in Denmark, in the same period as the 2013 International Conference on Aerodynamics of Offshore Wind Energy Systems and Wakes (ICOWES2013, 17-19 June 2013).

9.4.2 Subtask 8.2

The first aim of the Mexnext Annex phase II is to focus on the use of experimental data from previous measurement runs that have not been fully exploited[17]. A number of work packages were defined as in the first phase of the Annex, in order to study different different facets of rotor or wake aerodynamics. Different calculation runs will be defined, as well as the experimental data with which comparisons will be made. The energy research group at Gotland University will participate as in phase I to a work package related to near wake aerodynamics.

The new wind tunnel tests on the MEXICO model turbine should be performed in mid-2013, with improved instrumentation and Particle Image Velocimetry (PIV) capabilities relatively to the previous set of experiments. The goal will be to fill the gaps left in the first series of tests, where it should be possible to better calibrate turbulence intensity, better measure freestream velocity, and perform new aeroacoustic measurements. The wind energy research group at Gotland University intends to participate to the analysis of the data that will result from this new series of tests. The next Mexnext meeting should be held in Europe in September 2013.

9.5 Conclusion

Two annexes, named respectively Wakebench and Mexnext, have been put in place by the International Energy Agency in order to study wind turbine and wake aerodynamics. Use is made of experimental data, acquired either in the field or in wind tunnels under controller conditions, to validate simulation models. Comparison between the different models is also used in this process. The wind energy research group at Gotland University participates to both these annexes bringing together wind energy researchers from around the world n a joint effort to better understand wind turbine and wake aerodynamics..

Chapter 10

Conclusions

10.1 Achieved Results

The Nordic Consortium has during its three years existence further developed the Nordic collaboration within the wind farm and wake area. The different activities have increased the level of knowledge in everything from fundamental understanding of the wake spiral system to turbine interaction inside large wind farms and also to how large wind farms affect each other. In addition to that the understanding of how different levels of icing affect the power output and farm efficiency has been studied. Meso-scale simulation have been introduced which will become important when further looking into farm farm interactions since the scales then are clearly on a meso-scale level. Some of the projects (subtasks 5 and 7) were however started recently and are therefore in an initial stage.

An outcome from the project is also that a new KTH Wind Centre has been formed at KTH. The new centre is gathering wind power related activities at KTH and focuses on wind project development. An extension of the KTH Wind Centre is planned which will contain wind power project development activities at KTH, Gotland University and Uppsala University.

The main results from the project can be summarized as;

- Increased understanding of wake dynamics and breakdown

  The fundamental study of the spiral system and wake dynamics has resulted in a much greater understanding of the wake physics, based on both experimental and numerical work. Today we do understand the principal key questions to how and why the spiral system breaks down. What have been seen in wind tunnel experiments already 10 years back, i.e., the pairing of the tip vortices, can now be simulated and thereby one can study how fundamental parameters affect the wake physics.

  New numerical models for investigation of the instability growth rate have increased the efficiency of the stability evaluation. The result further showed that instability is dispersive and that growth occurs only for specific frequencies and mode types. The stability investigation also provides an evidence of a relationship between the turbulence intensity and the length of the wake. This is a result of fundamental studies (subtasks 1 and 2) of the wake properties combined with more applied studies where the model is verified (tasks 3 and 4). The equation below illustrates the relationship.

$$\tau = \frac{1}{\sigma_m}(-A - B log T_u) \quad (10.1)$$

where A and B are constants.

By a combination of a strong research environment in wind energy and flow stability the knowledge in the wake structure is on international frontline. The model that links turbulence level and wake length is a breakthrough. However, there are many questions remaining on how different parameters affect the model to be able to use this model on a daily basis for design and control of wind farms by industry.

- Verification of flow model
  The flow model was compared to model scale experiments within the IEA (International Energy Agency) Annex 29, the MEXICO project. The wake flow behind the MEXICO rotor was analyzed and used to validate the actuator line method. The analysis was based on five different flow situations, and the simulation results are compared to results based on PIV measurements performed on the MEXICO rotor. The tip speed ratio was varied for three of the cases and the rotor was yawed in two cases. Generally, a very good agreement was found when comparing the studied parameters (tip vortex core strength, bound circulation, streamwise and radial velocities as a function of the downstream distance from the rotor and the streamwise and radial position of the tip vortex cores, i.e., the tip vortex trajectory) determined in measurements and simulations.

  The tip vortex size was however found to be much larger in the simulations because we have a much lower Reynolds number, but the dependence of the results on the Reynolds number and on numerical parameters such as grid size and smearing of the ACL volume force has been analyzed in detail. The validation work will be used to improve the knowledge about how the results from ACL simulations are interpreted.

  Discussions within the MexNext Annex are currently being held and it is planned to establish a new measurement campaign. Future work will, if the measurements are available, be performed on the breakdown of the tip vortices in order to further validate the ACL method.

- Controller
  Within subtask 3 a controller has been implemented in collaboration with subtask 6 which is needed for a realistic power estimation but that controller is also the first step in the farm optimization. The control method is at this date implemented in the actuator disc method in EllipSys3D, and will in the near future be tested thoroughly in this environment. The next step ahead is to take this to the next level to implement a full farm controller.

- Accurate prediction of production variation in wind farms
  The results show that given specific parameters such as wind speed, turbulence level, boundary layer profiles etc. the power variation inside large wind farm is estimated with a high accuracy. The model could therefore be used for farm layout optimization and estimation of power production, fatigue loads etc. This high accuracy of the model is a result from joint research activities in subtasks 1, 2, 3, 4 and 6 since the fundamental understanding from tasks 1 and 2 is needed for the more applied studies in subtasks 3 and 4.

- A good basis for optimization of farms
  The simulated wake dynamics in large wind farms correlates very well with measurements. The first step in optimization is taken and derating of individual turbines has been implemented. The result shows that only derating the first row of turbines does not result in higher farm production, however, the fatigue loads will be effected by this change since the flow reaching

the downstream turbine has a weaker wake structure. The project is in a phase where CFD and structural loads can be combined for a full optimization of the farm control system.

To be able to control large wind farms very fast methods are needed for active control. Therefore, the models used in the controller need to be fast but also based on CFD simulations to ensure that the optimal settings are used in any potential situation. The project has resulted in verification of a fast vortex line model that could be used together with engineering farm control models developed in close collaboration with teknikgruppen.

A close collaboration has been established with the Swedish industry, for example Vattenfall and Scandinavian Wind. The project has resulted in a first step towards a farm optimization.

- Methods verified to be suitable for the continuation of icing studies

  The icing studies are in the initial stage but have reviewed what has been done in this area until today and initial studies have shown that proposed methods are suitable for further studies. The project has a good foundation to further studies in this area together with new partners with experiences of ice accretion on blade profiles.

- A good basis for continuation of farm-farm interaction studies

  The farm-farm studies are in the initial stage but have reviewed what has been done in this area until today and initial studies have shown that proposed methods and test simulations are suitable for further studies. The farm-farm interaction question will become more and more important. The review of performed work has indicated that there to a large extent is an interaction between large wind farms, also when they are spaced relatively far from each other. The research in this area is in its initial step and the coupling with meso-scale models will become important. Initial work has been prepared in that direction, both in collaboration with Kjeller Vindtekknik but also with Uppsala University and Weathertech Scandinavia.

  The ongoing PhD study has only been ongoing in the last period in this project and is therefore in its initial step. However, the first review and test simulation have been performed and a foundation for collaboration with meso-scale modeling has been created. Therefore, there is a good basis for future research in this field.

10.2 Remaining questions and future work

The computational capacity increases every day and that opens new possibilities and therefore new questions can be put on the table. Today, there are however still many questions remaining and even though the computational capacity increases we still need to make simplifications and approximations to be able to study the very complex situations that we do have when it comes to wind turbines operation in clusters in atmospheric boundary layers. However, the increased computational resourses open new possibilities and we may take new steps towards a more complete understanding of the complex physics. The main remaining questions in the area could be summarized as;

- Wake dynamics and breakdown
  The fundamental understanding of the wake spiral system using ACL methods in combination with large scale farm simulations with ACD methods does give us a good foundation to develop a trustable model for the wake length depending on a number of physical parameters. However, further investigations regarding how different length scale and structures in the turbulence affect the wake length and physics needs to be performed. The research is aiming at a model that could be used by the industry for farm design and control. The model for the prediction of the wake length developed so far in the project can be augmented with parameters describing further important physical mechanisms influencing the state of the wake.

- Farm-Farm interaction
  The Farm-Farm study started only one year ago so there is a great need for further understanding the farm-farm interaction as described above, in particular when it comes to meso-scale modeling predicting the influence of the variation of the atmospheric boundary layer on the wake of a wind farm.

- Complex terrain and forested areas
  The achieved results gives a foundation to further studies where the fundamental knowledge from performed studies is required. There is a great need to studies for Swedish conditions regarding complex terrain. The complexity does however grow with the number of parameters studied and when considering complex terrain and forested area, or even worse partly forested areas, or even combination of complex terrain and forested areas the complexity becomes clear. Also in this case, meso-scale models coupled with micro-scale models will be of high importance. Future research in this area is therefore essential.

- Icing
  The icing study started only one year ago so there is a great need for further research, however, as mentioned above, the project has good foundation for further studies. In particular, understanding the conditions under which various types of icing occur needs to be understood as well as what kind of influence the ice has on the aerodynamic properties of the wind turbine blades in order to be able to simulate farms affected by ice.

- Load predictions
  In recent years manufacturers have started to stress the need for more advanced analysis tools as the "product" has gradually changed from turbine to farm. Project developers and investors are today very concerned about loading and various options to control the wind farms. In some cases, commercial software,[35], or tools developed by research institutions, [12], can today be used for load predictions in situations where a majority of the turbines operate with constant

Ct. However, a full dynamic situation where all torque/pitch/yaw settings can be changed at any time (uprating/derating/stopping) cannot yet be handled.

A major task ahead is to develop a standardized way of extending future (and existing) aeroelastic codes to handle a situation where turbine simulations are run as parallel processes, in a two-way interaction with a chosen flow model. Here it should be possible to define the necessary interfaces in a way so that engineering flow models and CFD codes can be connected in a similar way. The Nordic Consortium and the international networks of the consortium partners here provide an ideal platform for a combined effort in this direction.

- Engineering methods
  The chain of engineering methods addressed within the current project has now reached a level where it is meaningful to take the next step, and use the flow description to connect 10-100 aeroelastic turbine simulations to a full wind farm analysis. During this process it will be invaluable to access results from CFD analysis of higher complexity and resolution, in order to make the right judgements when combining different sub-models.

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