GREETING

During the past two decades the wind energy market has become fully international. To appreciate an institution’s significance in the marketplace, one has to assess which value in terms of relevant knowledge and innovations is added to the developments as a whole. The more unique and application oriented the know-how an institution like ForWind has to offer, the stronger its basis for existence is. Another success factor is being part of key international and in particular, European networks.

During its relatively short existence, ForWind has managed to become a very active partner in crucial networks such as the European Technology Platform Wind Energy (TPWind) and the European Academy of Wind Energy (EAWE). This position, in combination with that of a provider of unique knowledge, has made ForWind a full-fledged partner in the European R&D community.

To better understand what that means, the achievements of ForWind have to be seen from the perspective of key trends in wind energy technology. The present situation is characterized by a sustained market growth of spectacular proportions (close to 30% per year during the last 7 years) and significant up scaling of both wind turbine dimensions and wind farm capacities. At the same time, the dream of installing wind turbines offshore as a way to avoid all forms of opposition against wind turbines on land has begun to materialize. Wind energy is quite visible by the energy balances of different countries, notably Germany, Spain and Denmark. (At the end of 2008, the total national electricity needs of Germany, Spain and Denmark were covered to 9%, 12% and 20% by wind energy.) Also on continental energy maps, wind energy can no longer be ignored. For the European Union and the world these figures are 3.7% and 1.3% respectively. These contributions were realized by 66 GW installed wind power in Europe out of 122 GW worldwide. 1.4 GW were installed offshore, all in European waters.

One comes to realize that we are at the brink of a new wind energy technology era if we compare our past achievements with what has to be achieved in the near future. The European Wind Energy Association foresees an installed wind power of approximately 180 GW in Europe by the year 2020, of which 20 to 40 GW are to be installed offshore. The European Commission considers these targets an essential contribution to its “20 – 20 – 20” objective (20% renewable energy, 20% more energy efficiency, 20% green house gas reduction by the year 2020). During the coming 12 years we have to install almost twice as many MW's compared to what we did in the past 30 years. Although the most recent installation rates (6.25 GW per year averaged over the last 4 years) do not dramatically differ from what is needed in the near future (9.5 GW per year during the coming 12 years), the consequences are quite dramatic. If we do not quantify the demands for raw materials, manufacturing capacity, manufacturing technology, installation and transport facilities, grid connection capacity, wind system concepts and last but not least, expertise, it is impossible to form a global picture of the necessary research needs.

Among various critical factors which were identified among others by the industry during the discussions of TP-Wind, the lack of “brains” stands out. In particular when it comes to bridging gaps between specific scientific and engineering disciplines from the wind energy technology on the one hand and generic disciplines like mathematics, material sciences, fluid and solid mechanics on the other, ForWind has shown its importance. The challenge for ForWind is to maintain this pioneering position in the future.

The present annual report 2008 is a fine illustration of how ForWind brings results from the scientific worlds of the Carl von Ossietzky Universität in Oldenburg and the Leibniz Universität in Hannover (energy meteorology, fluid mechanics, solid mechanics, civil engineering, electrical engineering, computer sciences) to the market place. This is an excellent starting position to maintain ForWind’s frontier role in new organizational wind energy research frameworks which are now developing in Germany.

Ir. Jos Beurskens
Chairman of the ForWind Advisory Board
PREFACE

Five windy years are now behind us: ForWind was founded in 2003 with the support of the Ministry for Science and Culture of Lower Saxony. During this time period, the wind energy sector underwent a dramatic transformation. Five years ago, wind energy was seen as a force to be taken seriously, however, its great significance for the energy supply had yet to be recognized in the mind of the public. The ongoing discussions on the finite nature of fossil fuel resources; on price development for fossil energy as well as on impending climate changes have created long-lasting repercussions concerning how the overall value of wind energy is perceived. In addition, the increase in efficiency in the production of wind-generated electricity has led to the view of wind energy as a success story: the world-wide growth rates are currently running at 20% or more per year. Moreover, this is a tendency which will continue in the coming years. The planned offshore wind farms promise a further great increase in potential.

Five years ago, engineers and scientists viewed wind energy research as one interesting new field of application among others. Despite large centers of research, particularly in Denmark and the Netherlands, the significance of wind energy research faced a lack of appreciation. That is all changing now: there is a great need for innovative solutions and new developments. Education and continuing education are in intensive demand – from students but also from experts and managers with the desire to qualify themselves to meet the requirements of the wind energy sector.

As a consequence, we find ourselves in a new situation: wind energy research has established itself and is developing into its own independent area of research which is the focus of more and more interest. ForWind is actively contributing to this: in 2009 the center will expand, welcoming the University of Bremen as a new partner. The Fraunhofer Gesellschaft has recognized the issue as trend-setting, not least due to the preliminary work of ForWind, and founded the Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES). Through IWES research groups, the cooperation between ForWind and the Fraunhofer Gesellschaft is to take hold.

Five lively and successful years are behind us, but the windy times are long from over. With the massive expansion of wind energy comes an increased demand for competent research. More reliable and effective wind turbines must be developed; that requires know-how in different areas of research – which we wish to demonstrate in this annual report. Contributing to the shaping and advancement of this development is especially important for the German Northwest. As one of the most prominent wind energy regions in the world, the location will continue to play a large role in the future for industry, science and education. This development will be actively shaped by ForWind in the years to come.

Prof. Dr. Joachim Peinke
Academic Speaker

Prof. Dr.-Ing. habil. Raimund Rolfes
Deputy Speaker

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1 According to data from the European Wind Energy Association EWEA, the global wind energy capacity increased by 28.8% in 2008. See: www.ewea.org
CONTENT

Greeting ....................................................................................................................... 2

Preface ......................................................................................................................... 3

1. The Organization ...................................................................................................... 6

1.1 Executive Board ................................................................................................... 6
1.2 Scientific Advisory Council ................................................................................. 7
1.3 Research Institutes ............................................................................................... 7
1.4 Associated Members of ForWind ........................................................................... 7

2. Research Center ..................................................................................................... 8

2.1 Turbulence Modeling and Turbulence Interaction (RP I) ........................................ 8
2.2 Offshore Meteorology (RP II) ................................................................................ 11
2.3 Wind Power Forecasting and Grid Integration (RP III) ......................................... 14
2.4 Environmental Loads on Offshore Wind Energy Converters (RP IV) ..................... 16
2.5 Fatigue Assessment of Support Structures of Offshore Wind Energy Conversion Systems (RP V) .............................................................. 19
2.6 Condition Monitoring and Damage Detection on Structures of Offshore Wind Turbines Using
    Measured Modal Quantities (RP VI) ......................................................................... 25
2.7 Modeling Soil-Structure-Interaction for Offshore Wind Energy Plants (RP VII) ....... 28
2.8 Grid Integration of Offshore Wind Energy Parks (RP VIII) ....................................... 32
2.9 Integrated Modeling of Offshore WEC (RP IX) ....................................................... 34

PART A: INTEGRAL MODELING OF THE SUPPORT STRUCTURE DYNAMICS .................   34
PART B: MODELING OF DYNAMIC LOADS ON WIND TURBINES ................................... 38
PART C: CFD-SIMULATION FOR LOAD CALCULATIONS FOR WIND TURBINES ........... 39

3. Competence Center ................................................................................................. 44

3.1 Development Projects .......................................................................................... 44

3.1.1 Evaluation of a Measurement Technique for Damage Detection on Rotor Blades of
    Offshore Wind Turbines (E1-07) .............................................................................. 44
3.1.2 Increase in Preload of Bolts in Joints of Wind Turbines by Application of the DISC™ (E2-07) ............................................................ 47
3.1.3 Harmonic Behavior and Thermal Load in the Rotor Winding of Doubly-Fed Induction Generators
    for Wind Turbines (DP3) (E3-07) ........................................................................... 51
3.1.4 Development Project ForWind-Academy: A Unique Offer for Academics to Obtain Qualification (E1-08) .................................................. 53
3.1.5 Analysis of Unsteady Flow on Rotating Wind Turbine Blades (E2-08) ......... 54
3.1.6 Novel Line-side Control Methods for Wind Energy Plants with Medium Voltage Converters (E3-08) ...................................................... 55
3.2 Other Projects

3.2.1 GROW – Grouted Connections for Offshore Wind Turbine Structures

3.2.2 Deutscher Windmonitor – German Wind Monitor: Characterization and Prediction of the Wind Field

3.2.3 WISENT – Wissensnetz Energiemeteorologie

3.2.4 Decentralized Energy Management (DEMS) Project – Wind Power and Load Forecast

3.2.5 Joint Research Project "Development of LiDAR Measurement Techniques for the German Offshore Test Site"

3.2.6 SCHALL 3 – Design, Testing, Realization and Verification of Low Noise Construction Methods and Noise Reduction Techniques During Construction of Offshore Wind Turbines

3.2.7 GIGAWIND alpha ventus – Holistic Design Concept for OEWC Support Structures on the Base of Measurements at the Offshore Test Field “alpha ventus”

3.2.8 OGOWin – Optimization of Jacket Foundation Structures for Offshore Wind Turbines Concerning Material Consumption, Assembling Order and Manufacturing Process

3.2.9 Adaption and Test of an Early Damage Detection- and Load Monitoring System for Glass Fiber Blades of Wind Energy Converters

3.2.10 Partner in the EU-Project POWER cluster

3.3 Continuing Studies Program Wind Energy Technology and Management

3.4 Events Hosted by ForWind

3.4.1 ForWind Course of Lectures

3.4.2 RAVE – Research At Alpha Ventus

3.4.3 "Wakes Measurements and Modeling within and Downwind of Wind farms: Current Features and Future Trends"

3.4.4 Science Meets Practice – Innovations for Wind Energy

4. Documentation

4.1 Publication List

4.1.1 Reviewed Articles

4.1.2 Reviewed Conference Contributions

4.1.3 Other Publications

4.1.4 Lectures at Universities

4.1.5 Project Reports

4.2 Diploma, Master and Bachelor Theses

4.3 PhD Theses

4.4 List of ForWind Staff Members

Imprint
1. The Organization

ForWind, the Center for Wind Energy Research of the Universities of Oldenburg and Hannover, combines scientific know-how with research geared towards the industry. ForWind bundles the competencies of both universities and is an adept industry contact. The administrative office of ForWind is located in Oldenburg.

ForWind was founded in 2003 through the support of the Ministry for Science and Culture of Lower Saxony. Since 2006, a formal agreement of both universities exists to form a corporate research center as a joint institution.

What continues to make ForWind unique in Germany is that it is a university institution serving to pass along its broad spectrum of expertise to the industry by way of cooperating projects. Within the industry, ForWind has established itself as a competent research partner.

1.1 Executive Board

ForWind is led by a four member executive board consisting of two members of the Carl von Ossietzky Universität Oldenburg and the Leibniz Universität Hannover respectively. All members have equal authority.

The current executive board is made up of:

Prof. Dr. Joachim Peinke
(Academic Speaker)

Prof. Dr.-Ing. habil. Raimund Rolfes
(Deputy Speaker)

Dr. Detlev Heinemann

Prof. Dr.-Ing. Peter Schaumann
1.2 Scientific Advisory Council

Chairman:
Beurskens, Jos, Ir
Energy research Centre of the Netherlands (ECN)

Members:
Clauss, Günther, Prof. Dr.-Ing.
Technische Universität Berlin

Hermesmeier, Jörg, Dr.
EWE Aktiengesellschaft

Hulek, Klaus, Prof. Dr.
Leibniz Universität Hannover

Molly, Jens Peter, Dipl.-Ing.
DEWI GmbH

Niemeyer, Matthias, Prof. Dr.-Ing.
Salzgitter Mannesmann Forschung GmbH

Schmid, Jürgen, Prof. Dr.-Ing.
Institut für Solare Energieversorgungs-technik e.V. (ISET)

Schneidewind, Uwe, Prof. Dr.
Carl von Ossietzky Universität Oldenburg

Schroeder, Hans, Dr.
Ministry for Science and Culture of Lower Saxony

Schubert, Matthias
REpower Systems AG

Ttworschka, Hartmut, Dr.
HOCHTIEF Construction AG

1.3 Research Institutes

The following institutes and research groups belonging to the Universities of Oldenburg and Hannover are active in ForWind:

Institute of Building Materials Science, Leibniz Universität Hannover, Prof. Dr.-Ing. Ludger Lohaus

Institute of Concrete Construction, Leibniz Universität Hannover, Prof. Dr.-Ing. Jürgen Grünberg

Institute for Drive Systems and Power Electronics, Leibniz Universität Hannover, Prof. Dr.-Ing. Axel Mertens and Prof. Dr.-Ing. Bernd Ponick

Institute of Electric Power Systems, Leibniz Universität Hannover, Prof. Dr.-Ing. Lutz Hofmann

Institute of Fluid Mechanics and Environmental Physics in Civil Engineering, Leibniz Universität Hannover, Prof. Dr. Insa Neuweiler

Institute of Physics, Energy Meteorology, Carl von Ossietzky Universität Oldenburg, Dr. Detlev Heinemann

Institute of Physics, Hydrodynamics and Wind Energy, Carl von Ossietzky Universität Oldenburg, Prof. Dr. Joachim Peinke

Institute of Soil Mechanics, Foundation Engineering and Waterpower Engineering, Leibniz Universität Hannover, Prof. Dr.-Ing. Martin Achmus

Institute for Steel Construction, Leibniz Universität Hannover, Prof. Dr.-Ing. Peter Schaumann

Institute for Structural Analysis, Leibniz Universität Hannover, Prof. Dr.-Ing. habil. Raimund Rolfes

1.4 Associated Members of ForWind

Endowed Chair of Wind Energy (SWE), Universität Stuttgart, Prof. Dr. Martin Kühn

Institute of Foundation Engineering and Soil Mechanics, Universität Duisburg-Essen, Prof. Dr.-Ing. Werner Richwien
2. Research Center

2.1 Turbulence Modeling and Turbulence Interaction (RP I)

Carl von Ossietzky Universität Oldenburg, Institute of Physics
Julia Gottschall, Hendrik Heißelmann, Pascal Knebel, Joachim Peinke

Description

This project is devoted to the impact of turbulence on wind energy converters. In particular we studied three different aspects, namely, the improved high frequency measurement of wind speed as a basic characterization of turbulent wind conditions, the dynamic stall as a typical interaction of wind fluctuations with the rotor, and the effects of turbulent wind fluctuations on the power output.

The first two aspects were pure experimental approaches and have led to the development of a new type of anemometer, which we call the “sphere anemometer”. This sphere anemometer is as simple as the cup anemometer but does not have moving parts and measures the wind speed more accurately. For the dynamic stall measurements an experimental set up has been developed which allows to change the angle of attack on a profile rapidly. Based on a contact-free measurement technique the overshoot of the lift forces and the onset of the stall effect could be measured dynamically. As a next step we have developed an active grid to generate typical turbulent wind fluctuations under laboratory conditions in the wind tunnel. Thus the impact of reproducible turbulent wind conditions can be investigated in our wind tunnel, which seems to be in this wind application unique worldwide.

For the third aspect we developed a new procedure to estimate the power characteristic from high frequency turbulent wind-power data. This work has somehow attracted most attention. The published paper was selected as one of the “Best of 2008” for the journal Environmental Research Letters (ERL). Also the PhD Student Julia Gottschall received the Young Wind Doctor Award of the EAWE 2009.

Activities

Further Development of Sphere Anemometer

The sphere anemometer makes use of the velocity-dependent displacement of a bending tube caused by the drag force acting on the sphere and its support. The high resolving light pointer principle, known from atomic force microscopes, is utilized to detect the displacement of the sphere. This makes the sphere anemometer a simple and robust sensor without any wearing parts. The velocity-induced deflection of the laser spot is detected via a two-dimensional position sensitive detector and can be related to the flow velocity by calibration.

During 2008 the first promising construction of the sphere anemometer was improved and characterized in detail. A streamlined construction of the anemom-

Figure 1: First prototype (left) and refined setup (right) of sphere anemometer.
The structural interaction of turbulent inflow conditions is known from helicopter aerodynamics. This effect is sometimes called Dynamic Stall.

A lack of measurements in comparable flow conditions make it difficult to give reliable predictions of the arising loads and load alternations acting on the blades of wind turbines (compare also report RP IX).

For the examinations of dynamic stall in the wind tunnel of the University of Oldenburg, the lift forces on airfoils are determined via 80 pressure gauges to determine the pressure distribution over the wall of the test section. The airfoil is rotated by a stepping motor.

In order to examine the impact of turbulent inflows an active grid has been constructed. It allows the creation of flows with high turbulence intensity, large turbulent structures and intermittent increment statistics of the velocity on large time and length scales, which is characteristic for natural wind fields. More detailed descriptions can be found in the former annual reports.

During the last year the programs (written in CVI and LabVIEW) for data acquisition, control of the active grid and of the airfoil, the wind tunnel control and the traversing system have been improved or recreated. This includes the implementation of ActiveX interfaces for the automation of different measurement schedules. The creation of sequences is done in Teststand, test management software of National Instruments that has been purchased for that purpose. Systematic examinations have become strongly simplified or become initially be possible by the automation process.

In the data acquisition, the data is written in ROOT-files. ROOT is a C++ class library and an object-oriented software for data analysis which has its own file format. ROOT is developed by CERN and originally designed for the data analysis in particle physics. It is open source software and available for any operating systems inclusive Windows, Linux and MacOS. Each ROOT-file can be organized in a directory like structure making it possible to store description data in addition to the raw data in a hierarchical way. One of the key features of ROOT is the handling of large amount of data. Before written in binary format to disk the data becomes compressed.

Due to the smaller required disk space, the data can directly be written to a network drive and in parallel to the acquisition analyzed on second computer. By these

![Figure 2: (a) Probability density functions for measured wind speed increments \( u(t+\tau)-u(t) \) for \( \tau = 5 \text{ s}, 15 \text{ s}, 30 \text{ s} \) from the bottom up, and (b) for the respective measured and reconstructed (grey, based on proposed dynamical Langevin model) power increments \( P_\tau = P(t+\tau)-P(t) \) for \( \tau = 15 \text{ s}, 30 \text{ s} \).]
developments inaccurate measurements can directly be detected and if needed repeated during the measurement period and so a more efficient use of the limited measurement time in the wind tunnel has been managed.

By an extension of the active grid setup in the last year the movement of the airfoil can now also be operated by the active grid control. Therefore in principal it has become possible to run non-sinusoidal driving profiles. An insufficient power of the stepping motor is the reason why up to now no stochastic moving patterns have been examined.

For the development of a phenomenological load model the lift coefficient has systematically been measured against the average angle of attack, the amplitude of the angular velocity and the amplitude of the angle of attack. As an outcome the maximum lift coefficient is increasing with increasing angular velocity and could be described by an exponential function in the measurement range. The rather small power of the stepping motor mentioned above is the reason for a relatively strong limited measurement range regarding the angular velocity and can explain why no absolute maximum of the lift coefficient could be found.

Additional measurements were performed for a more complete characterization of the active grid. This includes measurements of turbulence decay in dependence of the used forcing protocol and the incident wind velocity as well as measurements regarding the homogeneity of the horizontal velocity profile downstream the grid. Further on it has been achieved to create horizontal gradient velocity profiles with the active grid. In addition a new kind of forcing protocol was developed, that yields to better results concerning the desired flow properties than conventional forcing patterns do. Thus with this setup we are able to generate inflow conditions which are very similar to those in real wind situations. The advantage: with our setup we can perform well-controlled and reproducible experiments.

Analysis of Power Characteristics / Dynamical Power Curve Estimation

Already in former years, we introduced – based on considerations about turbulence effects on the process of wind power conversion – a method to determine the power characteristic of a wind energy converter (WEC) that is more efficient and more accurate than the standard method due to IEC 61400-12-1. The developed method is based on the theory of Langevin processes, describing the response of the WEC to the fluctuating wind as a stochastic process. Essentially, the method is characterized by its dynamical approach. In contrast to other conventional methods, the relaxation dynamics of the power output, i.e. the actual effective system behavior, is considered for the reconstruction of the relation between wind speed and power output defining the power conversion process. During 2008, we continued in validating the approach for numerical data and tested it for different sets of measured wind speed and power data. We also finished the joined project “Wind turbulences and their impact on the utilization of wind energy” that was funded by the BMBF for duration of three years during 2005 and 2008 (official code of funding: 03SF0314A). For our part in this project, the main emphasis was on reconstructing the effects of turbulence on the power conversion of the WEC. A crucial result is shown in Figure 2, illustrating the transfer of turbulent fluctuations in terms of wind speed and power output increments.

In parallel, the explicit procedure of estimating the dynamical power characteristic was further developed and important improvements were implemented in the respective algorithms. An advanced estimation of final uncertainties was developed and further design parameters were discussed.

Figure 3 shows the result of a “complete” power characteristic for a data set that was measured and evaluated in the framework of the above mentioned joined project.
2.2 Offshore Meteorology (RP II)

Carl von Ossietzky Universität Oldenburg, Institute for Physics
Abha Sood, Kay Sušelj, Detlev Heinemann

Motivation

The limitations in the current approach for offshore wind resource assessment are apparent since the extrapolation of boundary layer wind data from the sparsely distributed in-situ measurement sites is not representative. Therefore it is vital to ascertain the ability of the model simulations to adequately represent the marine boundary layer in more spatial detail by validating the results with high temporal and spatial resolution in-situ measurements. The model simulations in the future can then be used in lieu of expensive on-site measurements for better spatial coverage. The additional advantage of simulation data is that the long term information of the boundary layer characteristics for which no measurement data are available can be reconstructed from past climate data and computed for future climate scenarios.

For a more extensive investigation of some less well comprehended aspects of the offshore and coastal boundary layer wind field, a measurement campaign was launched in cooperation with the TU Braunschweig during the spring season of 2008 at the North Sea coast in north-western Germany and the FINO-1 platform with a Helipod turbulence probe mounted under a helicopter. The motivation was to detect and examine the deficits in the parameterizations used in the models in considerable detail, in particular, of the stable boundary layer which occurs for the cool sea – warm air conditions prevalent in particular during the spring season. In subsequent projects, a further improvement in the boundary layer parameterization on the basis of this assessment can be undertaken and the impact of the improved representation of the land-sea interface on mesoscale circulation pattern in the German Bight be examined and validated with measurements from the offshore, island and coastal meteorological stations.

The ongoing research efforts for this sub-project were focused in 2008 on conducting an in-situ measurement campaign over the coastal and the offshore regions in the German Bight, assessing the impact of long term past and future surface wind climates trends and their impact on the long term wind resource variability in the German Bight (MODOBS), measurements of multi-megawatt wind turbine wakes using turbulence probes.

Approaches / Activities

The structure of the boundary layer flow is related to the large scale circulation patterns as well as the correct representation of the surface conditions determined by e.g. orography, land use, surface roughness etc. The atmospheric boundary layer (ABL) flow is more complex over the land-sea transition zone due to the formation of coherent mesoscale land-sea breeze circulation triggered by abrupt changes in the surface roughness and thermal forcing.

In the following, we begin with investigating the sensitivity of the boundary layer flow to the surface forcing at the land-sea transition zone including the coastline, the islands, the near (< 10 km) and the far offshore regions and compare the in-situ measurement with high resolution mesoscale model (WRF) simulations.

References


measurements was taken at a square around the FINO-1 site also at three different heights.

Wakes from Multi-megawatt Wind Turbines and Wind Farms

The turbulent wakes produced by wind turbines modify the ambient wind conditions considerably for wind turbines within large offshore wind farms. In particular, wake structures from large 5-6 MW wind turbines at the onshore coastal wind turbine testing site in Rysumer Nacken west of Emden in the north-west of Germany. Measurements of the inflow and wake conditions at three heights were taken.

Long Term Variability

The North Atlantic Oscillation (NAO), which is described by the pressure gradient anomaly between the north-west Europe (usually Iceland) and south-west Europe (usually Azores) is known to have a strong influence on the surface wind climate over the northern Europe, especially during the winter season.

A similar regional spatial pressure pattern (SLP) has previously been derived which is shown to have a more dominant influence on the wind speed variability of the North Sea [1]. The variability of the North Sea 10 m wind speed (WS10) for the 59 years (1948-2006) period is mostly well represented by the low resolution NCEP reanalysis data due to high spatial coherency of the WS10 over the sea.

The relationship of the long-term large scale atmospheric circulation patterns related to the past and the future climate states are investigated with respect to its influence on the surface wind fields within the EU-Marie Curie RTN project MODOBS. The seasonal trend in wind speed for the past (1961-2000) and the future (2061-2100, SRES A2 scenario) period as predicted by the average of 29 ensemble members of 16 IPCC global circulation models is presented in Figure 2. A signal of an increase in the wind speed by a magnitude of 0.5-1 ms⁻¹ is captured over the North Atlantic and the North Sea mostly for the winter season whereas for the other seasons, the trend is very weak and inconclusive. Most though not all simulations show the same results: 80% of the model simulation show a change in the wind speed in the range presented.
in the middle and right column of Figure 2. Thus sustained wind energy resource is probably available in the North Sea region even in the future changing climate though not much is known about the distribution of the change, especially regarding the extreme conditions.

Figure 2: The change of the mean WS from past (1961-2000) to future (2061-2100) climate. First column: the GCM mean change derived from Projected Principle Components (PPC), second column: 90 percentile of WS change derived from Trend Principle Components of the SLP (TPC) and third column: 10th percentile WS change estimated from the PPC.
2.3 Wind Power Forecasting and Grid Integration (RP III)

Carl von Ossietzky Universität Oldenburg, Institute of Physics
Jens Tambke, Nadja Busch-Saleck, Jinhua Jiang, Thomas Petriagis, Miriam Wolff, Lüder von Bremen, Florian Bertsch, Detlev Heinemann

Description

The project “Wind Power Forecasting and Grid Integration” supports scientifically the development of tools and strategies for the integration of wind power into current and future electricity supply systems. The forecasting-group develops and evaluates different methods for the prediction of wind power in the range of 0-96 hours, aiming to achieve higher precision. In 2008, the forecasting-group started to develop a new, improved and unified forecasting model (written in Python), which will be released in 2009. It is based on the experiences with the commercially very successful system “Previento” and the research tool “Hugin”, both developed at ForWind in recent years. The new model can be run with input data from many different weather services. On ForWind’s website, a free online forecast is available, updated four times a day, and based on GFS-weather forecasts.

The quality of input wind data is crucially important for power prediction models. Thus, meso-scale modeling and ensemble predictions, which are a combination of several weather prediction runs or models, are used to get adequate wind predictions which serve as input data for the wind power prediction tools. Ensemble predictions realized by the combination of ECMWF’s, DWD’s and HIRLAM’s forecast model show a considerable improvement, especially in periods of low error correlation (spring and summer). The meso-scale Weather Research & Forecasting (WRF) model was installed and evaluated as part of the project WISENT. Results show still some positive biases which can be due to a lack of tuning. But overall, the performance of the WRF model is very encouraging.

The quality of the wind data first of all depends on the performance of numerical weather models as mentioned above. The correction of them using real time observations of wind speed or wind power provides the opportunity for a closer adaption to reality. Systematic errors and particularly phase errors that are caused by delayed or early predicted weather fronts can be lowered considering this data. Our forecasting group works on this topic and contributed to the project DWIND-Monitor.

Wind power predictions can be made available efficiently by online platforms. Those platforms and their underlying processes have been developed in the projects DEMS and WISENT. Our research group contributed to these projects with wind power and load predictions.

SafeWind

ForWind is a major project partner in the new EU-project SafeWind. This project deals with multi-scale data assimilation and advanced wind modeling and forecasting with focus on extreme weather situations.

In addition to deterministic power forecasts, there is growing interest in additional information like the uncertainty of the forecast or the probability of extreme weather situations which may cause cut-off events. To provide this information, ForWind’s improved power prediction system processes not only deterministic but also ensemble weather forecasts (e.g. the ECMWF-EPS) as well as output from combined prediction models.

In the framework of the new EU-project SafeWind, we apply enhanced data assimilation techniques to produce updated wind fields over Europe using new sources of observations and latest high resolution NWP. Extreme wind power prediction errors are detected with the help of the meteorological fields of wind vector, surface pressure and temperature to identify phase-shifts, strong intensification of low pressure systems, or potential cut-offs of wind turbines. The wind power forecasts are then updated based on a correction of the wind fields with the derived wind map. In addition, nudging of wind energy forecasts using real-time observations from different spatially diverse sources such as meteorological or wind farm data is used to produce a more detailed wind analysis.

The difference between the current and the forecasted wind field is exploited to compute wind speed increments. They enable to correct for intensification or local development of low-pressure systems. These increments are getting smaller with increasing forecast step to take the limited validity in time of the increment into account. The role of the weather regime is analyzed as well. In highly advective situations, the importance of increments decline more rapidly than in weather situations with local developments.

Special attention is paid to the detection of cut-off events and strong wind gusts. Ensemble Prediction Systems (EPS) are evaluated using temporally highly resolved observation data to determine the probability of extreme events in a certain time interval. Clustering methods will be applied to establish risk classes which will be applied to operational use.

The ECMWF’s forecast model computes a gust factor that is defined as the maximum wind speed at 10 m height that occurs since the last archiving step. This gust factor is not the best option to model gusts at hub height of modern wind turbines. In contrast to this, a derived gust factor at hub height is ideal to forecast the probability of cut-off of wind turbines in a certain time interval. An example of the current gust factor at 10 m height is depicted in Figure 1. It covers the time period of the storm Kyrill in Central and Northern Germany.

Validation data requires high sampling rates to observe wind gusts. Meteorological wind met masts equipped with sonic anemometer (e.g. FINO1) and LIDAR sys-
tems provide the most accurate observation of gusts in a very high temporal resolution. The development of the methodology to verify probabilistic gust forecasts with high-resolved observational data is the major step in this new approach. It gives insight into the possibilities to predict cut-offs of turbines more accurately.

Figure 1: Average Gust Factor [m/s] at 10 meters height. This ECMWF forecast has been initiated at 15-01-2007 12UTC and is valid for 69 to 72 hours. It shows the approaching storm “Kyrill”.
2.4 Environmental Loads on Offshore Wind Energy Converters (RP IV)

Leibniz Universität Hannover, Institute of Fluid Mechanics and Environmental Physics in Civil Engineering
Thomas Kossel, Martin Kohlmeier, Werner Zielke

Introduction

For the design of reliable and cost optimized offshore wind energy converters (OWEC), it is important, to have an exact knowledge of the environmental loads. A significant portion of them, especially in greater water depth, are from wave action. A profound understanding associated with a correct reproduction in numerical simulations is essential in order to gain satisfactory modeling results and a reliable design basis.

The software WaveLoads has been developed at the Institute of Fluid Mechanics. It is a simulation tool for the calculation of wave induced loads on hydrodynamically transparent structures such as monopiles, tripods and jackets of OWECs. The implemented approaches for sea state modeling and calculation of wave loads have been presented in the previous annual reports.

The latest activities have focused on the integration of WaveLoads in simulation frameworks. The different processes and their interactions can now be observed in integral OWEC simulations. In these frameworks WaveLoads serves as a load generation module and can be used as finite element preprocessor. New features have been implemented to further improve the load calculation.

The Offshore Code Comparison Collaboration (OC3) of the International Energy Agency (IEA) has provided the opportunity for code-to-code verification and simulation result comparison. The simulation results from the finite element approach using WaveWeights for model setup and load generation are compared to results from established codes as well as to other newly developed codes.

Simulation Software WaveLoads

The software WaveLoads is a simulation tool for the estimation of environmental loads due to waves on offshore wind energy converters. The water particle kinematics, surface elevation and wave loadings can be computed for the following wave theories [1]:

**Regular Waves**
- Linear wave theory (Airy)
- Stokes 2nd, 3rd, 5th order wave theory
- Stream function wave theory by Dean, Sobey or Fenton

**Irregular Waves**
- 1-D sea state (based on Airy or Stokes 2nd order)
- Wave kinematics estimation based on prescribed water surface elevation

Figure 1: Calculation steps in WaveLoads
Constrained model with embedded individual extreme wave

2-D sea state including waves traveling in different directions of prescribed distribution

The loads are calculated from the resulting wave kinematics using the Morison equation [2].

WaveLoads’ interfaces to finite element programs provide model data, load input and calculation commands for ANSYS®, MSC Nastran® or Abaqus®. A complete transient analysis with adjacent post-processing can be performed without user interaction. With this approach (Fig. 2) using WaveLoads and ANSYS the calculations for the OC3 project (see below) have been performed.

The required interfaces to integrate WaveLoads as a load generation module in simulation frameworks are provided by a dynamic link library (DLL). It can be directly linked to other applications such as multibody simulations and finite element applications or be used in graphical user interfaces for visualization of wave kinematics. Program communication can be performed through files or by direct data exchange. For further details see research project IX.

Activities

After in-house validation of WaveLoads using measurements of the research platform FINO 1 and the measurement mast Amrumbank West (see previous reports) the Offshore Code Comparison Collaboration (OC3) gave the opportunity for further research [3].

OC3 operates under Subtask 2 of the International Energy Agency (IEA) Wind Annex XXIII. It gives the opportunity of code-to-code verification and simulation result comparison [4, 5, and 6].

The NREL 5MW baseline wind turbine [7] is combined with different support structures. The results presented here are calculated with the turbine mounted on a tripod substructure with fixed foundation in 45 m water depth. Wind and wave directions are the same, the upwind leg points directly into the wind. For each structure different load cases with increasing complexity were defined to allow easy identification and elimination of errors such as modeling errors, errors in the code or inaccuracy resulting from different applied theories. Load cases without wind loads enabled the finite element approach using WaveLoads and ANSYS to participate in the result comparison (Fig. 3, left). In this approach the turbine and rotor blades are modeled as mass points without the need of a coupled aeroelastic simulation module.

The simulation approach using WaveLoads /ANSYS showed fairly good results right from the beginning. The further development and integration of new features led to very good agreement with the final results from other codes in the modal analysis as well as in transient analysis of different load cases. Two exemplary time series of...
internal forces from a load case with 8 m wave height and 10 s wave period are depicted in Figure 3.

In the process of improving the simulation approach, the following features have been implemented in WaveLoads:

- In addition to loads due to water waves, the calculation of buoyancy loads has been implemented into WaveLoads, thereby taking into account the dynamic water pressure.
- Coarse discretization near the water surface can lead to erroneous wave loads. WaveLoads overcomes this problem through detailed integration of the load on the respective members with consideration of the submersion depth.
- Loads on tapered members – especially from waves – are very sensitive to the discretization of the structure. WaveLoads can calculate locally refined loads in a dual mesh approach and integrate the loads to the structure elements geometries.
- Overlapping beam sections of the structure lead to wrong buoyancy and mass calculations as well as overestimated wave loads in the joints. WaveLoads identifies these joints and calculates buoyancy, mass distribution and wave loads correctly.

Overall simulation results are discussed in detail by Nichols et al. [5] and Vorpahl et al. [6]. In conclusion, great improvements by all participants have been observed.

As a general modeling issue the shear deflection appears to be important when the relative displacements of different sections of the structure affect the distribution of loads. This was observed at the tripod and will most likely be of the same effect for jacket structures. The problem can be overcome using Timoshenko elements rather than Euler-Bernoulli elements.

Conclusion

This report presents the further development of the simulation approach using WaveLoads and its interface to finite element tools. WaveLoads is used as load generator as well as a preprocessor setting up the finite element model and scripting the solution and post-processing phase. The whole simulation process is executed without further user interaction.

The newly integrated features of calculating buoyancy loads resulting from dynamic water pressure and considering the overlapping of beam elements in respect to buoyancy, mass distribution and wave loads proved to be a valuable extension.

Detailed integration of loads at the water surface as well as in tapered members through a local dual mesh approach lead to a more accurate load calculation and allows the use of rather coarse structure discretizations.

All these improvements are reflected in the calculated results in the OC3 project that compare very well to the results from the other participants’ codes and approaches.

References


2.5 Fatigue Assessment of Support Structures of Offshore Wind Energy Conversion Systems (RP V)

Leibniz Universität Hannover, Institute for Steel Construction
Peter Schaumann, Stefanie Steppeler

Introduction

Support structures of offshore wind energy conversion systems (OWECS) are designed for a lifetime of about 20 years. They are exposed to high dynamic loadings caused by wind and waves and have to resist about $10^9$ load cycles. Therefore, fatigue resistance becomes relevant for providing secure service time and economic design of OWECS. As a result of growing turbine capacity and adverse offshore conditions construction details like bolted connections (Fig. 1) that are involved in the load transfer need to be checked for fatigue in detail.

The proof of fatigue strength of ring flange connections is subject of intensive research activities at the Institute for Steel Construction [1], [2] and [3] in recent years. In Germany, tower constructions of OWECS are designed according to the BSH guideline [4]. A number of theoretical and experimental investigations have focused on perfect ring flange connections with ideal geometry. The existing design models have been developed on basis of perfect ring flange connections.

There are uncertainties in the evaluation of the influence of imperfections and the tolerable fitting accuracy like shown in Figure 2. Previous investigations of Jakubowski [5], [6] and [7] have shown the influence of the unavoidable imperfections caused by production. But until now, in the field of research there is no final clarity of tolerances which have to be complied with. In current design and construction practice the deviations from plane prescribed by the manufacturers of tower segments are accepted and used.

Figure 1: Ring Flange Connection between Tower Segments of a Wind Energy Converter
In the framework of this research project the deviations of the ring flange surface from ideal plane were measured at an exemplary ring flange. Two measurement techniques were compared.

**Measuring Object and Task**

The measuring object is the head flange of the upper tower segment of a wind energy converter (see Fig. 3), which is later connected with the gondola. The tower segment has a length of about 19.0 m and the diameter of the head flange is 3.0 m. The connection flange, which is connected to another tower segment, has a diameter of about 4.3 m.

The ring shaped surface of the head flange, which can be seen in Figure 4, has a thickness of about 200 mm. The tower segment was bounded on two shells located round 1 m from each ring flange plane.

The measuring task is the determination of the deviations of the ring shaped surface of the head flange from ideal plane. Two measurement techniques have been compared.

**Measurement Techniques**

Measurement techniques deal with methods and equipment to determine physical values experimentally. In the present case 3-D coordinates of the ring flange surface shall be measured in order to identify the planeness of the surface after the manufacturing process. Two common measurement systems will be compared: On the one hand the optical measurement technique of the close range photogrammetry and on the other hand a laser technique. Both are shortly described in the following based on [8], [9], [10], [11], [12] and [13].

**Laser Measurement Technique**

The laser measurement technique of Easy-Laser® can be used in order to determine the deviation of each measuring point.
from a reference plane. The location of this plane in space is unknown.

The Easy Laser D600 Machine System is used. The equipment is mounted with magnet bases onto the measurement object and consists of a motor driven laser transmitter, a detector with SpinLaser Technology and a meter reading unit.

The laser beam is continuously rotated 360° by a motor driven laser transmitter. A reference plane is built up over the ring flange surface by setting three zero points at intervals of 120°. Only the detector has to be moved around the ring flange to record the measurement values at the selected positions. The laser transmitter sends a laser signal to the detector and the value of the deviation from the reference plane of each measurement point is stored in the meter reading unit.

For evaluation the data has to be transmitted from the meter reading unit to the computer in the EasyLink Software. The program flange is used to evaluate the planeness measurement. 48 measurement points, spread over the whole ring flange, are used in case of the ring flange measurement (24 measurement points at the outer and 24 measurement points at the inner annulus of the ring flange).

Close Range Photogrammetry

The close range photogrammetry is an optical measurement technique. The position in space of an object is determined with measurement pictures.

The close range photogrammetry measurement is performed with the digital camera Nikon D80 and the software PhotoModeler®. Coded targets are placed at the object and photos are taken from different views. The software analyses the measurement pictures via triangulation and calculates the 3-D coordinates. The result is a point cloud with 3-D coordinates, which can be exported for further evaluation. Two yardsticks with geodetic calibrated targets are placed in the picture to define scale in the model.

Afterwards, the 3-D coordinates are exported from PhotoModeler®. The deviation from plane is computed by the software Geomagic Qualify®. Via adjustment theory the ideal plane of the ring flange surface is suited in the given point cloud of measured 3-D coordinates. The deviation of each measuring point from the ideal plane of the ring flange surface is the result of the measurement.

Comparison

In Table 1 the close range photogrammetry and the Easy-Laser® measurement system are compared. The 3-D coordinates of the close range photogrammetry allow a more detailed evaluation of the measurement results. The data of the Easy-Laser® measurement are the values of deviation from plane without any coordinates. In case of the quality inspection the values of deviation are adequate, but for investigations into detail the 3-D coordinates are necessary.

With regard to the fact that all tower segments that leave the fabrication shop have to pass this quality inspection, the time factor becomes relevant. The expenditure of time of the Easy-Laser® measurement is very low in comparison to the close range photogrammetry measurement. The close range photogrammetry measurement has to be planned and prepared, measurement pictures have to be taken and evaluated with the software.

The application of the close range photogrammetry system is complex in comparison to the Easy-Laser® system. On the one hand different software has to be used and on the other hand the measurement itself has to be performed. There are more sources for errors in the close range photogrammetry system.

The resolution of the Easy-Laser® system is given with 0.001 mm by the producer. The accuracy of the close range photogrammetry system depends on the equipment, camera settings and the field situation.

<table>
<thead>
<tr>
<th>Measurement System</th>
<th>Close Range Photogrammetry</th>
<th>Easy-Laser®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Value</td>
<td>3D Coordinates</td>
<td>Value of Deviation</td>
</tr>
<tr>
<td>Expenditure of Time</td>
<td>high</td>
<td>low</td>
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<tr>
<td>Application</td>
<td>complex</td>
<td>simple</td>
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<tr>
<td>Accuracy</td>
<td>depends on Equipment, Camera Settings and Field Situation</td>
<td>0.001 mm (given by the producer)</td>
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Figure 5: Easy-Laser® Measurement at SIAG Anlagenbau Finsterwalde GmbH

Figure 6: Close Range Photogrammetry Measurement at SIAG Anlagenbau Finsterwalde GmbH
Measurement Performance

The in situ measurement took place at the fabrication shop of the tower segment manufacturer SIAG Anlagenbau Finsterwalde GmbH. Both measurement techniques were performed on the same head flange.

Easy-Laser® Measurement

The Easy-Laser® measurement was performed by two employees of SIAG Anlagenbau Finsterwalde GmbH as illustrated in Figure 5.

At first the reference plane was built up. Afterwards, the detector was moved around the ring flange manually to record the 48 measurement values continuously spread over the ring flange. At each of the 24 control points two measurement values were taken: one at the outer and one at the inner annulus.

After the measuring process, the data was transmitted to the EasyLink Software. Via best fit analysis the result plot with the measured data and the deviation from plane was given.

Close Range Photogrammetry Measurement

The measurement with short-range photogrammetry was performed by the Institute for Steel Construction. 252 prepared coded targets (84 per inner, middle and outer ring) were applied to the surface of the head flange and two yardsticks were placed like shown in Figure 6. Two spotlights were positioned for ideal illumination. The photos of the upper part of the head flange were taken from a portable rack. The camera was positioned on a tripod.

After the preparation, the ring flange surface was divided into sections covered in three photos, each taken from a different point of views (frontal and from both sides). The analysis of the measurement pictures was performed by the software PhotoModeler® via triangulation. Therefore, a camera calibration with the current camera settings is required. The point cloud of 3-D coordinates was computed and exported to the software Geomagic Qualify®. The deviation of each measuring point from the ideal plane of the ring flange surface was computed via adjustment theory.

Results

The measurement results of both measurement systems are shown in Figure 7. The deviations from plane are displayed over the angle on the ring flange.

Easy-Laser® System

The curves of the Easy-Laser® measurement of the inner and outer ring have approximately the same shape. The deviation from plane reaches from -0.23 mm to 0.17 mm. The total maximum overall deviation is 0.40 mm. Furthermore, the results show that the maximum difference between inner and outer ring of measurement value is 0.10 mm.

Close Range Photogrammetry System

The curves of the close range photogrammetry measurement of the inner, middle and outer ring have approximately the same shape. The deviation from plane reaches from -3.59 mm to 3.62 mm. The total maximum overall deviation is 7.21 mm. Moreover, the results show that the maximum difference between inner and outer ring of measurement value is 1.25 mm.
Comparison

First of all it can be seen that the values of deviation of both sets of curves differ very strong. The deviations from plane of the close range photogrammetry measurement are much higher than those of the Easy-Laser®. There is a potency of ten between these of the Easy-Laser®. It is assumed that the connection of the used camera does not connect the lens to the body of the camera stable enough. Furthermore, the inner orientation of the camera is not stable during the measurement because of the unstable lens. This instabilities cause a systematic error of the image coordinates. There is a displacement of picture elements in the direction of gravity. The error in the present range of accuracy is high. For further investigations the use of a more stable lens and lens connections is recommended.

The effect of gravity to the lens and the development of mathematical methods to compensate this effect are subject of current research work in the field of geodesy.

Evaluation and Outlook

The close range photogrammetry measurement differ very strong from the Easy-Laser® measurement. This is caused by the lens and the lens connection of the used camera. Therefore, the comparison into detail of the results of both measurement systems was not possible.

The Easy-Laser® system is an accepted measurement system for tower segment manufacturers with high accuracy. The application is fast and simple. Despite the high expenditure of time and the complex application, the close range photogrammetry can be recommended in order to investigate the deviation from plane into detail. To improve the measurement results of the close range photogrammetry system another measurement phase should be arranged in the future.

References


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2.6 Condition Monitoring and Damage Detection on Structures of Offshore Wind Turbines Using Measured Modal Quantities (RP VI)

Leibniz Universität Hannover; Institute for Structural Analysis
Johannes Reetz, Wolf-Jürgen Gerasch, Raimund Rolfes

Description

Future wind turbines and offshore wind turbines in particular will require large periods of maintenance and standstill periods will lead to extensive financial effects. A condition-controlled maintenance of supporting structures of those wind turbines requires a damage detection system with remote monitoring.

A damage detection system has to diagnose small changes of the supporting structure including a quantification and a localization of the damage. The model based identification method mentioned in [1] bases on the “Multiparameter Eigenvalue Problem” (MPEWP). The method is generally applicable to elastomechanical systems, whose dynamic behavior is sensitive to changes of the system, e.g. changes of stiffness or masses. An advantage is the minimal expense for the measurement.

The following activities are primarily concerned with tests on real supporting structures of wind turbines and the adoption of the method on special problems of wind turbines.

Activities

Lab Models

In the annual report 2006 tests on lab models were described. In order to continue and to complete these tests, further tests under improved conditions had been carried out. In particular an aim was to determine the best measurement capability of the modal analysis.

The vertical cantilever beam with an elastic end-restraint had a height of two meters and consisted of five bolted segments of flat-bar steel. In order to apply defects, some segments had been replaced with segments with a smaller stiffness. The frequency spectrum of the model with frequencies from \( f_1 = 1 \text{Hz} \) to \( f_4 = 45 \text{Hz} \) was similar to the frequency spectrum of real wind turbines. The lab-model was excited by an electro-dynamic shaker, see Figure 1 and the signals were measured by means of a laser sensor. The use of the shaker enabled pulse excitation and also stochastic as well as harmonic excitation. The harmonic excitation provided following advantages: The accuracy of the signals related to the duration of the measurement is high and it enables an optimal selection of the measuring point for each eigenfrequency (EF), respectively. An improved mounting of the model on the ground floor had led to more constant dynamic properties of the model.

The results of these tests are 24 EF with an accuracy of three decimal places, four EF for each damage condition including the initial condition, respectively. The replacement of segments with those of a decreased stiffness had led to further five conditions.

Firstly the results show that at least four EF are measurable with an accuracy of three decimal places. It is an advance compared with the results from pulse excitation. Secondly the different damage conditions leads to changes in the first decimal places of the measured EF. So the changes of EF caused by damages are highly larger than the best measurement capability.

Rotor Blade

In order to apply the method to further components of wind turbines and whose defects, a rotorblade is being investigated. Just now a dynamic measurement cam-

Figure 1: Electro dynamic shaker exciting a lab model and measured frequency spectrum with an eigenfrequency of 1,225 Hz
Figure 2: Diagnosis of an “out-of-tune”-system by means of EF, measured on a guy wire tower construction of an operating wind turbine

Wind Turbine with Guy Wires

In order to test the method under real conditions, an in-situ measurement campaign had been carried out on a wind turbine with guy wires, see Figure 2. The investigations focused on the accuracy of the method under in-situ conditions, on the effective influence of modification of stiffness on the dynamic behaviour, and on the sensitivity of the method using it for real supporting structures of wind turbines.

For this purpose the supporting structure was “put out of tune” within limits of load capacity. The initial tension of the lower guy wires as well as the upper guy wires had been changed stepwise. The outcome of this was six different damage conditions. These conditions led to different EF. The aim was to diagnose the damage conditions by means of the measured EF. Acceleration sensors had been used for measurement with quasi-stochastic excitation.

Results are four several EF of the supporting structure for each of the six damage conditions, respectively. This measured EF has an accuracy of nearly two decimal places. The results of measurement correspond approximately to previous calculations. The expected influence of the damage conditions on the dynamic behaviour could be verified. Again, the changes of EF caused by damages were larger than the best measurement capability. It could be shown that changes in the condition of the supporting structure, which not affected the load capacity, could be detected by means of a minimal expense of sensor technology.

References


Closing investigations and evaluations will show, which damage conditions will be localized and quantified and how sensitive the method will be using it for real supporting structures of wind turbines.

Truss Tower

There is a further measurement schedule for truss towers for wind turbines. This year the method is being tested on those structures. The grade of bolting will be changed in several parts of the structure stepwise and the modal quantities of the tower will be measured. Again the outcome of this will be EF depending on the damage conditions, respectively. The evaluation of these investigations will show how far the method can be used on truss towers for wind turbines.

Damages of Foundations

In order to adapt the method to a current problem, similar investigations are planned on wind turbines with damages at their foundation. Several wind turbines with different failure modes will be investigated. The evaluation will have been shown, in which state of damage damages can be detected and diagnosed.

Simulations and Applications

At present, the method is adapting on problems of foundations. Investigations of sensitivity by means of simulations are carried out and possible results of measurement are estimated.

Scour

A very similar problem exists if scour occurs on offshore windturbines. Investigations show that also scour influences the dynamic behavior of offshore structures [2]. The model based identification requires numerical models. A numerical model had been generated with the aim of further investigations in this field and the application of the method for scour problems.

Validation and Identification

As mentioned before, the formulation of the identification problem as a MPEWP leads to numerical issues with relatively large dimension. Actions had to be taken concerning to software as well as hardware.

E.g. there had been a gap between the available workspace and the precision of the numerical models depending on the finite element meshing. So workspace was increased and models were generated, which take the characteristic influences on the dynamic behavior into account. With it numeric models were corrected by means of using the MPEWP for validation. These models keenly reproduce the measured EF of the original structure and hence whose dynamic behavior.

Outlook

With the approach of a model-based identification method and its application on the field of structural health monitoring, simulations, model tests and in situ tests had been carried out. In order to investigate the sensitivity, to apply the method to several supporting structures and to adapt the method on special problems of wind turbines, further simulations and tests are carrying out in the future.
2.7 Modeling Soil-Structure-Interaction for Offshore Wind Energy Plants (RP VII)

Leibniz Universität Hannover, Institute of Soil Mechanics, Foundation Engineering and Waterpower Engineering
Martin Achmus, Khalid Abdel-Rahman

Description

Object of the project VII is the numerical modeling of the behavior of foundation structures for offshore wind energy converters (OWECs). For that static, quasi-static cyclic as well as dynamic loads are to be considered. The working steps foreseen for the five year-duration of the whole project are shown in Figure 1.

In the first year numerical models for the monopile foundations have been established and their behavior under static loads has been investigated. In the second year of the project this work was continued and parametric studies were carried out regarding this aspect. Furthermore numerical models for suction bucket foundations were established and the performance of such foundations was compared to that of monopiles.

During the third year, a parametric study of suction buckets with different diameters and penetration depths was performed. Also a three dimensional numerical analysis of tripods under horizontal loading was carried out. In the fourth year the behavior of piles under combined axial and vertical loading for cohesive and non-cohesive soil was examined. Then a numerical scheme to predict the behavior of monopiles under cyclic loading was developed and implemented in the finite element code. In the last year the stiffness degradation model was applied for the pile-soil system and the rigid clamping concept was examined. Finally the effect of the pile stiffness on the pile behavior regarding the recent horizontal loading was numerically examined. The results are summarized in the following sections.

Activities 2008

Application of Stiffness Degradation Model for the Pile-Soil System

The numerical procedure using Abaqus (2008) [1] for the consideration of the stiffness reduction for the pile-soil system is elucidated in Figure 2. In a first step, the loading of the system by the weight of the tower structure and the soil is analyzed. With that, the initial stress state of each element of the discretized system is gained.

In the third calculation step, the horizontal load is applied again, but the stiffnesses of the soil elements are adopted dependent on their stress history. With that, for any number of load cycles N the system behavior can be calculated by a recalculation of the second step using appropriate stiffness values.

A problem in the application of the stiffness degradation model for the pile-soil system is a reasonable definition of the initial stress state and the cyclic load level for each element of the discretized system. On one hand, the initial stress state is not isotropic, and on the other hand the principal stress orientation changes during loading and the minor principal stress does in general not remain constant.

To overcome these problems, the following scheme was chosen to derive a characteristic cyclic stress ratio: For the initial stress state (Index (0)) as well as for the state under action of the cyclic load (Index (1)) a stress ratio $X_{st}$ is calculated:

$$X_{st}^{(0)} = \frac{\sigma_{1}^{(0)}}{\sigma_{3}^{(0)}} \quad X_{st}^{(1)} = \frac{\sigma_{1}^{(1)}}{\sigma_{3}^{(1)}}$$

The cyclic stress ratio $X$ is then calculated by

$$X = \frac{X_{st}^{(1)} - X_{st}^{(0)}}{1 - X_{st}^{(0)}}$$

This parameter $X$ characterizes the increase of the stress level in each element under cyclic load. Values $X < 0$, which may arise due to a decrease of deviatoric stress from the initial to the loaded state are not taken into account, i.e. in such cases the soil stiffness remains unchanged.

The degradation parameters have to be determined in a series of cyclic triaxial tests see (Achmus et al. 2007a) [3].
Results of the Numerical Modeling

In Figure 3 the relative increase $w_N/w_1$ is given for the four systems considered and compared with the approach of Hettler (1981) [5]. Tendentially his approach is confirmed. However, the model results show that the rate of deformation increase is not constant, but depends on the system. For medium dense sand the rate is higher than for dense sand and for $h/L=1$ it is higher than for $h/L=0$. Thus it seems that the rate of accumulation is dependent on the relative load level, i.e. the ratio of the actual to the ultimate load of the system.

Finally, in Figure 4 the results of numerical calculations for monopiles with a diameter $D=7.50$ m and a moment arm $h=20.0$ m with varying embedded lengths are given. For comparison reasons the calculations were done for dense and medium dense sand. It can be seen that the piles with longer embedded lengths have a smaller accumulated rate of lateral displacement. This means that increasing the embedded length of the monopile is an efficient way to resist large accumulated displacement under cyclic loading. For more details, refer to Achmus et al. 2007b [4].
On the Rigid Clamping Criterion

Up to now, in the design of horizontally loaded offshore piles “rigid clamping” was usually required. This means that for the loading under consideration, the pile deflection line should exhibit two zero deflection points or a least a vertical tangent at a certain depth below the point of rotation. This requirement stems from the idea that a pile clamped in the soil in this way will be relatively insensitive to cyclic loading. For offshore piles of usual diameters up to 2 or 2.5 m, this requirement has proved to be reasonable. However, for very large diameters and thus very stiff monopiles this requirement leads to very large embedded lengths. As can be seen in Figure 5, even the monopile with L=40 m does not fulfill the rigid clamping criterion.

Figure 5 compares the lateral deflections for two different piles (D=7.5 m and 2.5 m) under the same loading conditions. The monopile with larger diameter exhibits a lower rate of accumulated lateral displacement than the pile with smaller diameter, but this pile does not demonstrate the rigid clamping behavior. On the contrary, a monopile with a smaller diameter has a larger lateral displacement accumulation and thus a worse cyclic performance, but it exhibits a rigid clamping effect. Hence the suitability of using clamping length for a monopile design under long term cyclic loading needs to be reviewed (Achmus et al. 2008 [2]).

In the stiffness degradation approach, only one load combination is considered, i.e. constant load amplitude. In fact, wind and wave loads acting on an OWEC of course vary.

Regarding the application of the stiffness degradation in practice, the following approach can be used: Amplitude spectra of both moment and horizontal force at mudline should be provided. From these spectra a reference load (the maximum load) has to be defined and the equivalent number of cycles has to be determined. From the spectra distinct load classes (characterized by Hk, hk and respective Nk for each class) must be derived. Since the load classes are defined, the equivalent number of load cycles Nk* of the reference load can be calculated by an approach proposed from Lin & Liao (1999) [7]:

\[
N_k^* = N_1 + \sum_{k=2}^{n} N_k^*
\]

(4)

Herein w_{1,1} is the static displacement under reference load, w_{1,k} is the static displacement under the load of different amplitude and Nk is the number of cycles of this load. The parameter t is a degradation parameter, which is besides others a function of soil properties and loading type (one-way or two-way loading). For one-way loading t is a value of the order of 0.20 according to Lin & Liao (1999) [7]. The static displacements for a given load H and height of loading point h can be determined using the force-displacement curves obtained for static loading.

Summing over all loads of different amplitudes (load classes), the resulting equivalent number of load cycles of the reference load is

This method has exemplarily been applied for a monopile D=7.5 m, L=30 m embedded in dense sand under specific wave loading conditions. A wave spectrum derived by Mittendorf et al. (2004) [8] for a 12-year time period at a specific North Sea location was taken and the loads were determined using the Morison equation. Seven load classes were defined. The loads, the number of load cycles and the resulting equivalent load cycles with respect to the maximum load are shown in Figure 6. The results indicate that over the considered 12-year period an accumulated deformation is to be expected, which is about 43 % larger than the static displacement under the maximum load.

The results also indicate that the influence of low wave heights is neglectable, which seems rather plausible. Of course, this method is not yet experimentally verified and yields thus only an estimation of accumulated displacements. However, no other approved method to predict accumulated displacements with respect to specific loading and soil conditions yet exists.

Figure 5: Comparison of clamping effect in piles with different diameters (Kuo, 2008) [6]
Figure 6: Exemplary application of the method of Lin & Liao (1999) [7] for a monopile D=7.5 m, L=30 m in dense sand (t=0.17)

\[
w_{\text{geo}} = 4.53 \cdot (1 + 0.17 \cdot \ln 12.82) = 1.43 \cdot 4.53 = 6.48 \text{ cm}
\]

**References**

2.8 Grid Integration of Offshore Wind Energy Parks (RP VIII)

Leibniz Universität Hannover, Institute of Electric Power Systems, Division of Power Supply
Lutz Hofmann, Chanchai Amornvipas, Jörn Runge, Ara Panosyan

Description

Until 2008 the research activities of research project VIII were divided into two main sub-topics:

• Wind energy generators and their control
• Grid connection and operation

Work on these two research topics started in 2005 and was continued and further extended in dependence on the progress and appearance of new challenges. The research activities on the above-mentioned topics were completed in 2008. The final results are described in the PhD thesis “Modellierung von Windenergieanlagen für die Netzberechnung” [1] and in a further PhD thesis which will probably be finished in 2009.

In 2008 activities changed and based on further results the influence of wind energy generators (WEG), HVDC connections and FACTS elements (Flexible Alternating Current Transmission Systems) on the power quality were investigated. Particularly the power system resonances, which are within the harmonic spectrum of the WEG, HVDC and FACTS elements, were analyzed.

This work was also finished in the end of 2008, the results are described in the PhD thesis “Harmonic Studies and Resonance Analyses in Electrical Power Systems” [2].

Since end of 2008 work was focused on the comparison of the transmission behavior of different transmission systems. This will be continued in 2009, first results will be published in the ForWind annual report 2009.

Activities

Wind Energy Generators and their Control

With their growing share in the overall electrical energy generation the influence of wind turbines on the electrical power system’s behavior increases. Analyzing this impact and the modeling of wind turbines which is necessary for such an analysis is the scope of this study. Within the efficient framework of the electrical energy system’s Three-Time-Scale-Character all wind turbine components required for network calculations were generally modeled. Based on transient models which can be used for studying short circuit events, possible model reductions could be described and discussed by considering necessary time resolution and time constant compensation. Frequency converters used for control and their protection systems impact the transient processes in particular in case of short circuit events. The reduced order models derived in this thesis can be used for simulating processes activated in case of wind gusts such as the pitch-control. Accordingly, these models are also employed for primary control studies. Stationary wind turbine models were derived for power flow computation methods. The modularly developed component models allow simulations and analyses of all common generator systems. Such simulations and analyses have been carried out exemplary for squirrel cage induction generators, doubly fed induction generators and permanent magnet synchronous generators. The development of suitable control algorithms and analyzing fundamental simulations enabled a demonstration of the basic ability of modern wind turbines to sustain voltage and frequency stability under ordinary conditions and short circuit events. This basically leads back to the high control performance of the modeled frequency converter technologies employed for turbine control and connection.

Grid Connection and Operation

Most of today’s power transmission systems were designed to serve vertically integrated utilities, where the local electricity load demand was matched by local generation. Power therefore was transferred over relatively short distances, from large power plants to the load centers. Whereas large long-distance power transfers between interconnected systems were usually reserved either for predetermined amounts of power flows between the interconnected systems, or for emergencies, such as unexpected generation outages and sudden loss of power. This limited use of long-distance connections hence served system reliability.

The liberalization of the electricity market has lead to the increase in power transfers from low-cost generation areas to the load centers, which consequently resulted in an increase in the demand for power exchange over long distances between different parts of the power system. The emergence of ever larger unpredictable renewable energy sources like large-scale wind parks, which are typically located near the weak parts of the system far away from load centers, has further increased the strain on the transmission system and stretched it closer to its capacity limits. In order to face these growing challenges on the power system and ensure a stable and reliable power supply, transmission systems must be modernized to increase its capacity and efficiency to meet the rising demand, and flexibility to better react to more diverse generation and load patterns.

Upgrading and reinforcing transmission systems are traditionally done by expanding the system with new transmission lines. The process to permit and build new transmission lines is however extremely difficult, expensive, time-consuming, and controversial. It is therefore necessary to look for alternative technologies that enable a better utilization of the existing transmission systems and hence increase the reliability and security of the power system. Power electronics based equipments and systems, like HVDC (High Voltage DC)
and FACTS (Flexible AC Transmission Systems), are currently the key innovative technologies, which provide adequate solutions to the new system challenges, by increasing transmission system capacity and enhancing the operation and control of the entire power system.

In order to study the behavior of HVDC and FACTS and their impact on the power flow and node voltage, the steady state models of thyristor-based HVDC (“Classic”) and FACTS (SVC, TCSC, TCPS) have been previously developed. These were later complemented by the models of the new converter-based HVDC (“PLUS”, “Light”) and FACTS (STATCOM, SSSC, UPFC, IPFC), which were subsequently developed, and added to the simulation tool. The different models were conclusively tested both separately and in combination with other non-conventional devices on simple test systems. The different control modes of each device were also implemented and its effect on enhancing the system capacity and control were analyzed.

Harmonic Studies and Resonance Analyses in Electrical Power Systems

Harmonics are considered to be one of the power system disturbances causing voltage and current waveform distortions due to the undesired high-frequency components. Not only power quality, but also power system operation can be negatively affected by harmonics. Important sources of harmonics are power electronics controlled devices which have been increasingly used for diversified purposes in electrical power systems in the recent years. In the work of 2008, harmonic problems due to Voltage Source Converters (VSCs), FACTS and WEG were studied in detail.

In addition to the modeling of harmonic sources, the modeling of power system elements is important for analysis of harmonic propagation into power systems. To serve this purpose, the frequency domain modeling of transmission lines and transformers must be accurately done for the frequency range up to some kHz. The frequency-dependent parameters of the models have to be taken into account due to the skin effect. Under the assumption of symmetrical harmonics in balanced systems, harmonic analysis is generally carried out with the single-phase based symmetrical components. However, systems in operation are often unbalanced. In those cases, it is necessary to investigate harmonics in the original three-phase system. For different calculation purposes, the power system elements need to be modeled in the single-phase based symmetrical components and in the original three-phase system.

In order to analyze harmonic problems effectively, system resonant behavior in addition to harmonic sources has to be investigated. For determining the system resonant frequencies and analyzing resonances in steady-state, the practical method of Resonance Mode Analysis (RMA) in the modal coordinate system is suitable. By using the knowledge obtained from the modal admittance sensitivity analysis, it is possible to improve the system resonant behavior by selective modification of the network configuration, such that the critical resonances will not excited by the problematic harmonics.

References

2.9 Integrated Modeling of Offshore WEC (RP IX)

It was the goal of the project to develop tools for a holistic modeling of Offshore Wind Energy Converters. Specifically, the project was to provide an integrated modeling system of the system dynamics including the aerodynamic and hydrodynamic loads, the support structure and the rotor.

This final report, which consists of three parts, shows that the targets of the project have been accomplished. In Part A the main features of the integrated modeling system are summarized. It has been shown that it is operational and can be applied in further research. Part B concerns the aerodynamic loads with methods which have been used in the integrated modeling. Part C presents supplementary results from high resolution CFD computations of the aerodynamic loads.

PART A: INTEGRAL MODELING OF THE SUPPORT STRUCTURE DYNAMICS

Leibniz Universität Hannover, Institute of Fluid Mechanics and Environmental Physics in Civil Engineering
Martin Kohlmeier, Thomas Kossel, Werner Zielke

Introduction

The aim of research project IX is to meet the demand of integral simulation of offshore wind energy converters (OWEC). The integrated modeling approach has been developed, in order to incorporate the research results of the ForWind projects. With the realization of the integrated model (IM) the diversity of different processes and process interactions within offshore wind energy turbines and its associated subsystems have been taken into account. In this section, part A of research project IX is presented. It focuses on modeling the support structure dynamics including the environmental loads, the rotor blades’ aero-elasticity and a simplified representation of gear box, generator and control system. A flexible structure of the integral model has been developed. Its well designed object-oriented structure with an easily extendable set of modules and interfaces meets future demands.

Approach: Overview and Final Status

The concept of the integrated model takes into account the needs of various ForWind projects and incorporates their research results and some of the simulation tools which they have developed. The key aspects can be summarized as follows: Programs used by the research teams are of different programming languages. Their data are of inhomogeneous formats. A fast data exchange is required in advance or during the simulation process.

The most important development has been the realization of sub-model interactions. With the chosen strategy, the interface capabilities of the framework itself have been increased continuously in a step-by-step approach: (i.) independent modules in terms of self-contained tools, (ii.) iterative-ly coupled modules with file data exchange and (iii.) fully coupled modules with direct data exchange. A short overview of the development is given in the following:

During the years 2005 and 2006, the following independent models have been developed. They are the basis for current integrated modeling:

a. Visualization and export of environmental loads due to prescribed regular waves or sea states using the program WaveLoads [1].

b. Usage of the aerodynamic loads module AeroDyn (v.12.56) [2] in combination with the modal / multibody dynamics module FAST (v.6.01) [3].

c. Development of visualization tools and an input data description module for user-friendly software operation.

d. Comparisons of results based on different simulation strategies depicted in Figure 1.

e. Further development of dynamic link library (DLL) applications of the wave load module (Wave Loads) regarding multibody input data generation in order to simplify multibody OWEC simulations using MD Adams® (Fig. 4).

The development of iteratively coupled modules benefited from the cooperation with MSC Software Corporation initiated in 2005. The resulting developments till 2007 have been as follows:

a. Supply of geometric and material data in combination with distributed loads for elastodynamic analysis with finite element programs (ANSYS®, MD Nastran®, Abaqus®).

b. Combination of wave load analysis (Wave Loads) with wind load modeling (AeroDyn) in multibody OWEC simulations using MD Adams®.

In 2007, first coupled modules have been applied in the integral model approach:

a. Application of the developed dynamic link library (DLL) of the wave load module (Wave Loads) combined with the DLL of the wind load module (AeroDyn) in multibody OWEC simulations using MD Adams®.

Within the current and final reporting period of 2008, the above mentioned development has been continued successfully (Fig. 1 and 2) and extended by the following features:

b. Static and dynamic fluid pressure integration for incorporation of buoyancy loads in finite element or multibody analysis.

c. Improvement of the finite element approaches using the tripod support structure defined in the international code-to-code comparison project OC3 [8, 9].

d. Comparisons of results based on different simulation strategies depicted in Figure 1.

e. Further development of dynamic link library (DLL) applications of the wave load module (Wave Loads) regarding multibody input data generation in order to simplify multibody OWEC simulations using MD Adams® (Fig. 4).
Figure 1: Schematic representation of the integral modeling framework

Figure 2: Schematic representation of the software interaction for integral modeling of wind and waves acting on the offshore WEC. The resulting MD Adams model is dynamically linked to the environmental load modules AeroDyn and Wave Loads. The resulting internal forces can be used for further static or dynamic finite element analysis.
Activities

The integrated model (IM) has been successfully completed with emphasis on the elastodynamic analysis of the support structure. This implies a fully aeroelastic and hydrodynamic simulation package with loads from waves and wind. It is composed of self-contained components which have been developed independently and are combined with control, data base and interface units. The modular concept enabled the independent code development of each research team. The program is written in an object-oriented language (C++) using the cross-platform application development framework Qt® for the development of multi-platform graphical user interfaces (GUI). The GUI of the IM as well as its included modules and data base tools [4] have been developed independently and thus can easily be adopted for their use in further applications.

The resulting fully integrated simulation approach is performed as follows: First, the modules FAST and WaveLoads are applied independently. In this preprocessing step, the data sets needed for multibody simulations are generated, namely the multibody representation of a WEC and an offshore support structure model as depicted in Figure 3. After combining both data sets, a multibody simulation can be performed using DLLs for the aeroelastic part, for the generator, the pitch control, and for the wave loads, respectively. The equations system representing the resulting multi-body dynamics problem is assembled and finally solved within MD Adams® as depicted in Figure 4. With increasing amount of integrated sub-modules it is useful to have graphical assistance available. Here, the integration of DLL based modules in graphical user interfaces (GUI) provides a user-friendly input data management and data visualization.

The applicability of this approach has been verified in two steps: First, the validation of the aeroelastic module is satisfied, because the validated FAST/AeroDyn software is being used. Secondly, the wave
loading module applied in a finite element approach (WaveLoads/ANSYS, [6]) has been verified within the international Offshore Code Comparison Collaboration (OC3), see RP IV for more details. The results are very satisfying as described also by Nichols et al. [8] and Vorpahl et al. [9]. Having these data available enables the assessment of all remaining simulation approaches depicted in Figure 1.

With the described integrated model approach, nonlinear effects resulting from nonlinear couplings can now be studied. The aeroelastic and hydrodynamic damping can be investigated in order to study the effects of simultaneously occurring wind and wave loads and to quantify the sensitivity to their direction. A set of turbulent wind fields generated within part B of this research project has been successfully applied. In case of dynamic stall investigations to be performed, the results of part C of this research project can enhance the simulation capabilities of the current framework.

Finally, all necessary developments have been performed to enable simulations of a 5 MW prototype wind turbine [7] mounted on a tripod support structure as depicted in Figure 3. A reliable formulation of the interaction mechanism between support structure and foundation has to be incorporated in the model. For this purpose, the soil pile interaction investigated in RP VII can be numerically described and implemented in this model framework.

Summary
A fully integrated aero/hydro-elastodynamic simulation package for OWECs has been developed. All necessary processes of the turbine and its systems for rotor and generator control are included as sub-modules. Within this package, simulations of different complexity can be performed: Firstly, a finite element approach incorporates several preprocessing techniques, wave load generation and elastodynamic simulation. Secondly, in a more flexible approach, each sub-module is represented by a dynamic link library that can be applied and validated individually. With the combination of these sub-modules, the simulation of the whole OWEC is performed in a multibody set-up. Therein, an aeroelastic wind turbine model is mounted on an offshore support structure model. Turbulent wind fields interacting with the rotor are applied and wave loads from different sea states acting on the support structure can be modeled. Standard generator and pitch control models are included. This fully coupled multibody simulation can easily be set up for new designs of OWEC structures offering the opportunity to perform efficient optimization and sensitivity studies.

Figure 5: Atmospheric wind time series measured at the GROWIAN site in different heights (see: Part B)
PART B: MODELING OF DYNAMIC LOADS ON WIND TURBINES

Carl von Ossietzky Universität Oldenburg
Institute of Physics
Tanja Mücke, Joachim Peinke

Introduction

Wind turbines are exposed to the turbulent inflowing wind field. This atmospheric turbulent inflow leads to various kinds of loads in the whole system, especially on the wind turbines rotor. Atmospheric wind fields are characterized through a height increasing mean wind speed and randomly turbulent wind speed changes (see Fig. 5, p. 37). Thus, the rotor is always rotating through partial gusts. This so called rotational sampling has an important effect on the wind turbines fatigue strength.

Commonly, the turbulent wind speed variations were considered to be roughly Gaussian distributed such as in the often used IEC Kaimal model [10]. However, analyzing atmospheric wind field data with respect to the increment statistics shows, that the atmospheric wind time series are not Gaussian. The distributions of atmospheric velocity fluctuations are intermittent; they are characterized by marked fat tails and a peak around zero [11]. As increments directly measure the velocity difference for a time, intermittency means here that more extreme velocity fluctuations occur in measured wind fields than in simulated Gaussian ones. This property of real wind field data leads to more stronger partial gusts and with it to higher alternating loads on the wind turbine.

Numerical Modeling

For our research we use the dynamics program FAST [12] with the embedded aerodynamic subroutines of AeroDyn [13]. The FAST (Fatigue, Aerodynamics, Structures and Turbulence) code is a comprehensive aeroelastic simulator capable of predicting both the extreme and fatigue loads of two- and three-bladed horizontal-axis wind turbines. The numerical simulations of the wind turbines response are performed with an adapted model of the virtual 1.5 MW turbine designed as part of the WindPACT study [14]. For our application the wind turbine has a diameter of 70 m and a hub height of 87.5 m. Because of our interest in small scale turbulence the rotor speed and the pitch angles are fixed with 20 rpm and 4° respectively.

Activities

So far we have implemented the aerodynamic code AeroDyn in combination with the modal / multi-body dynamics module FAST. We verified the including subroutines and the resulting loads. Furthermore we calculated the dynamic loads for different wind turbines with Gaussian inflows according to the IEC Standard 61400-1. During the last year we have advanced the used methods and prepared new important procedures for the RP IX:

- Characterization of high-frequented turbulent wind data, measured in a grid of 100 m x 76 m at the site of the GORWIAN wind turbine [15].
- Analyzing these data sets with respect to the increment statistics.

Figure 6: Rotor torque fluctuations $Q_t$ for $t=1.2s$ resulting from numerical modeling with two different kinds of synthetic wind fields in comparison with the fluctuations resulting from measured GROWIAN wind fields. The results are all normalized to the standard deviation $s=1$
– Development of a program to integrate the GROWIAN wind field data sets into the load calculations with FAST/AeroDyn.
– Calculation of the rotor torque for a 1.5 MW wind turbine resulting due to atmospheric and two different kinds of wind field models firstly IEC Kaimal, generating Gaussian distributed wind fields [16] and secondly new developed model based on continuous time random walks generating intermittent wind fields (see RP I) [17].
– Estimation and comparison of the occurring torque fluctuations as measure for the different alternating loads.

Results

From the GROWIAN data pool, altogether 100 data sets with a mean wind speed of 9.72 m/s and turbulence intensity of 7.72% were selected. Evidently, the statistics deviate from a Gaussian distribution. In atmospheric wind fields, the probability of extreme changes of wind speeds is significantly higher than in the simulated standard IEC Kaimal model. That means, Gaussian wind fields don’t reproduce the extreme events of atmospheric wind fields. Furthermore, the characteristics of the inflowing wind field have a direct effect on the wind turbines response (see Fig. 6). On small scales, the resulting torque shows more extreme fluctuations by an atmospheric inflow than by a simulated Gaussian one. Hence, using purely Gaussian distributed wind fields leads to an underestimation of the occurring alternating loads. In contrast, the synthetic intermittent wind fields (generator was developed within the RP I, 2006) reproduce the alternating loads resulting from atmospheric data in the right way.

Figure 7: Change of angle of attack at 10 Hz for different wind turbine concepts at a measured wind field

PART C: CFD-SIMULATION FOR LOAD CALCULATIONS FOR WIND TURBINES

Carl von Ossietzky Universität Oldenburg
Institute of Physics
Berhard Stoevesandt, Wided Medjroubi, Nils Kirrkamm, Joachim Feinke

Motivation

A main source for loads on wind turbines are aerodynamic forces caused by the turbulent wind field on the turbine in general and on the blades in particular. Turbulence in the wind and flow separations on the blades lead to fluctuations of the loads on the blades, which sometimes experience a strong temporal increase in loads in such a way. Such load increases can further be transmitted onto the whole turbine structure.

Precise, time resolved models to capture the wind and load characteristics correctly are therefore becoming increasingly important. Nevertheless, time resolved computational methods for fluid dynamics are still a field of development. Therefore, we test and use advanced methods to gain generalized knowledge about the flow and the loads on the blades.

The focus lies on the investigation of unsteady phenomenon such as the dynamic stall or three dimensional effects on rotating blades. The dynamic stall effect is caused by sudden wind speed or direction changes as well as by other disturbances of the incoming flow on the airfoils. This can lead to sharp fluctuations of lift and drag on airfoils. Thus higher loads on the blades are induced, causing loads on all other parts of the turbine.

Calculating the real loads regarding dynamic stall is a broad field for scientific research. So far, the models rely up to now mainly on wind tunnel measurements for single airfoil sections or on computational fluid dynamics (CFD) simulations. While the first only allow assumptions on single airfoils for a specific experimental
setting, the disadvantage of the latter is the insufficient resolution of the unsteady turbulent effects with most standard CFD simulations. So far CFD calculations are not used as a standard method to investigate dynamic stall. High order methods, such as the spectral elemental method, are an approach to overcome the difficulties with highly unsteady effects in fluid simulations. We aim to make such approaches available for wind energy research.

Activities

Estimating the Changes in Angle of Attack

To achieve a realistic picture of the dynamic stall for wind turbines, the patterns of the changes in the angles of attack on the blades – or for research reasons airfoils – is of large interest. These have been analyzed under the estimation of wind turbine concepts of a constant tip speed ratio or a constant rotational speed at short time periods.

Figure 8: Double log. plot of the standard deviation or maximum values of the changes in angle of attack over the time increments

Figure 9: Turbulent kinetic energy around an airfoil using a 3D spectral element calculation

Figure 10: Pressure coefficient cp along the span wise direction of the airfoil
The turbine turning at a constant tip speed ratio is expected to rotate at an averaged wind speed of the last 2 seconds, while the turbine moving at a constant speed rotates at 20 rpm. The position of the analysis is in the middle of an estimated 40 m blade [18]. The changes in angle of attack due to wind speed and directional changes are shown in Figure 7 (p. 39). Analyzing the time periods (increments) in which the changes appear shows a relation of the standard deviation to the time increments being of $\delta \sim \tau^{1/3}$ making it obvious, that the fluctuations are no Wiener process (Fig. 8). This means that more fluctuations appear at smaller time scales, than a standard Gaussian process would consider.

A. Airfoil Simulations Using Spectral Element Method

We obtained the spectral element code from the imperial college in London. Since simulations on airfoils using this method are scarce, a first test of the code on an fx79-w151a airfoil has been performed. We used the direct numerical solver at a Reynolds number of $Re=5000$. The third dimension was calculated by a Fourier-expansion.

As the flow along the blade is mostly laminar only the very tail is of further interest for the analysis of the turbulence. Figure 9 shows the turbulent kinetic energy of the flow around the blade showing high values in the wake of the blade due to a “von Karman”-street like flow separation. This leads to turbulent flows at the tail of the blade causing fluctuating loads in that range. This can be seen in Figure 10 depicting the pressure coefficient along the span of the airfoil.

B. Body Motion and Dynamic Stall

For the research of the dynamic stall, different approaches have been evaluated. Since the effect is based on a movement of the airfoil against the flow field different mathematical approaches could be used. In case of the “Nektar”-Code an Arbitrary Lagrange-Eulerian (ALE) method and a method of a body motion by coordinate...
transformation have been tried out. Due to the enormous calculation time of the ALE method the latter has proven to be more applicable to the problem.

Using this method a blade in heave and pitch motion was analyzed at a Reynolds number of Re=10000 using a NACA-0012 airfoil. This motion causes a dynamic flow separation known as dynamic stall. Typically the loads on the blades undergo a hysteresis loop. As the flow at such Reynolds numbers triggers a typical von Karmen vortex street like vortex separation. A pitching blade moving at a similar time scale leads to a lock-in effect, which causes increased loads on the blades. To investigate the flow processes for possible chaotic behavior this is being done for different frequencies of the blade motion.

Due to the high computational time of the spectral element method, the analysis of the lock-in effects have so far been done using a 2-D simulation. Nevertheless first steps are also being done for a 3-D simulation.

C. Three-Dimensional Effects

Another unsteady effect on the blades of wind turbines is the so called delayed stall due to a vortex separation at the blade root. By the rotation of the blades such vortices are being forced along the blades towards the outer part of the blade causing a flow separation behavior which again leads to higher loads. Such effects can only be reasonably investigated using unsteady solvers which are able to simulate the rotation of the turbine.

For this the open source code OpenFOAM has been chosen to investigate such flow patterns. In a first step the simulation of the NREL-Phase VI experiment has been chosen for a first evaluation.

Outlook

Time resolved CFD simulations reveal a lot of information on temporal loads induced on airfoils by the flow. Time periods and amplitudes will be a further research topic, especially focusing on the effects caused by fluctuating inflow. As these effects are not only expected to appear on simple set-ups, like a single airfoil section in a laminar or periodic flow, further research on loads in realistic fluctuating flow is to be done. The simulation of whole rotating blades is going to proceed and will be extended to different solver types.
Annual Report 2008

References


Further Literature:


3. Competence Center

3.1 Development Projects

3.1.1 Evaluation of a Measurement Technique for Damage Detection on Rotor Blades of Offshore Wind Turbines (E1-07)

Leibniz Universität Hannover, Institute for Structural Analysis
Stephan Zerbst, Wolf-Jürgen Gerasch, Raimund Rolfes
Partner: HBM - Hottinger Baldwin Messtechnik GmbH
Duration: 2007 – 2008

Introduction

Recurrent damages occur due to manufacturing failure on composite blades. Web failure as well as joint failure between the two shells lead to serious damages that have to be repaired which causes time of standstill. Structural inspections of turbine blades are fairly rare, especially bad weather will obstruct the access to offshore structures. For this reason it is very likely that damages can grow and stay undetected too long. Therefore embedded monitoring systems for structural damage detection are developed, that on the one hand can help saving and optimizing the structure from dimensioning on and on the other hand can help achieving the maximum energy output by reducing and minimizing times of standstill. A new smart sensor system is currently developed within this project together with HBM. This system will be tested for damage detection on offshore wind turbine blades and will be designed for typical composite damage types.

Approach / Activities

Together with HBM a new sensor for deflection measurement is tested, that will replace accelerometers for blade monitoring in future. It consists of an active unit placed at the root section and a passive unit placed far inside the blade, both connected with a tensed fiber string. The advantage of the new sensor system is that it is absolutely insensitive to lightning strike because of no wiring and non-metallic components. Embedded into this project it will offer a deflection signal that can be transferred to a velocity signal much easier than accelerations can be transferred to velocities. Mounted inside a blade at a test site this new sensor is investigated concerning its mechanical reliability and signal-accuracy.

The monitoring strategy is based on a proportionality method which also has to be tested concerning its consistency in practice. Of high interest is the behavior of the damage-indicator over time and its sensitivity inside the method for early damage detection. Beside measurements also simulations will be done which deal with the same scenario of constant conditions during a fatigue test. During fatigue tests an exciter is shaking the structure near the resonance frequency in edge- and flapwise direction. The blade is moved in resonance with its first eigenfrequency separately in each direction. That means the optimal stress and velocity sensor locations are in line with the theory for damage detection [1, 2].

As a result of the curvature of the blade the deflection sensor cannot be mounted to the tip because the access from the inside is impossible and the string between active and passive unit would touch the shell. This means the sensor location for maximum velocity must be moved to a accessible place away from the tip.

Interim Results

FE-simulations have been done to investigate how sensitive the method reacts when damages like web failure occur. For that reason a harmonic excitation is applied and velocity and stress are calculated at different locations (Fig. 1 and 2).

Figure 1: Harmonic loading-direction and location

Figure 2: Sensor locations for flapwise investigation
Several scenarios have been observed, with length of single web failure between 1,5 m up to 5,0 m. Figure 3 and 4 show where the failure is applied to the root section located where the influence of bending is most intensive.

It is obvious that damages can be detected much better using the proportionality method than using the change of eigenfrequency as an indicator, because the percentage change of the proportionality is more than factor 10 higher. Especially scenario B shows a mean sensitivity in damage detection for section C and D (Tabl. 1 and 2).

After the first prototype of deflection sensor showed a good performance in recording reliable signals, nevertheless the mounting strategy had to be improved. The second prototype of deflection sensor is now mounted to glass fibre feet laminated to the web (Fig. 6) for secure durable installation instead of standard two-component-glue (Fig. 5).
Outlook

Current measurements are done that will document the consistance of the proportionality factor over more than 4 million cycles during a fatigue test on a blade test site. A second prototype of deflection sensor also is proofed to be reliable over a blade’s lifetime. Next steps are the mounting of a third prototype inside an operating turbine blade somewhere in Germany. Additionally further simulations will be done to show the sensitivity of the method applied to other typical damage scenarios.

References

3.1.2 Increase in Preload of Bolts in Joints of Wind Turbines by Application of the DISC® (E2-07)

Leibniz Universität Hannover, Institute for Steel Construction
Peter Schaumann,
Stephan Lochte-Holtgreven
Partner: Hytorc - Barbarino & Kilp GmbH, Munich
Duration: 07.2007 - 06.2008

Introduction

Bolted connections in wind turbine structures are mainly used for the connection of tower sections or blade and nacelle (see Fig. 1, left). The connections are exposed to high dynamic axial loads. Therefore fatigue assessments have to be carried out. For the design loads of bolts in ring flanges a non-linear relationship between the bolt force and the force in the flange has to be considered (see Fig. 1, right). For fatigue reasons the preload in the bolted connection has to be guaranteed.

The effective preload of a bolted connection is influenced by the surface and friction conditions of bolt, nut, washer, and mainly by the torque tool used. Investigations at the Institute for Steel Construction, of Leibniz Universität Hannover show that preloads in bolts of the same single manufacturing lot differ for different torque tool systems (hydraulic or electrical). To increase the reliability of the connection the scatter of the preload has to be reduced. HYTORC invented the bolt washer DISC®.

Regarding the scatter of the preload of high strength bolts the influence of the DISC® is investigated in this development project. Additionally different preload levels and coatings of the DISC® were tested.

Function of the DISC®

The HYTORC DISC® replaces the washer under the nut and is a two component member. The outer section is a high raised washer. The inner section is a thread section which is pressed into the outer section. Due to an inner ribbing of the washer the inner member can only be moved in axial direction.

Testing Series and Test Setup

Tightening tests with the DISC®-system were carried out. For reference conventional bolt assemblies were tightened too. These tests should show the effect of the shear forces in conventional preloaded bolted joints. The test series are summarized in Table 1.
Table 1: Testing series

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>number of tests</th>
<th>torque [Nm]</th>
<th>yield strength [f_y,b,k]</th>
<th>reaction arm</th>
<th>DISC coat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>conventional M36</td>
<td>15</td>
<td>2.800</td>
<td>0.70</td>
<td>yes</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>conventional M36</td>
<td>15</td>
<td>3.400</td>
<td>0.85</td>
<td>yes</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>M36 with DISC</td>
<td>15</td>
<td>2.700</td>
<td>0.70</td>
<td>no</td>
<td>hot-dip galvanized</td>
</tr>
<tr>
<td>4</td>
<td>M36 with DISC</td>
<td>15</td>
<td>3.300</td>
<td>0.85</td>
<td>no</td>
<td>hot-dip galvanized</td>
</tr>
<tr>
<td>5</td>
<td>M36 with DISC</td>
<td>15</td>
<td>2.450</td>
<td>0.70</td>
<td>no</td>
<td>bolt coat</td>
</tr>
<tr>
<td>6</td>
<td>M36 with DISC</td>
<td>15</td>
<td>3.050</td>
<td>0.85</td>
<td>no</td>
<td>bolt coat</td>
</tr>
<tr>
<td>total:</td>
<td>90 bolts</td>
<td></td>
<td></td>
<td>f_y,b,k = yield strength</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Besides the nominal preload according to the standard DIN 18800-7 [1] an increased load of about 85% of the yield strength of the bolt material was tested. All tests were carried out on a ring flange section typical for a wind turbine tower. The bolt elongation was measured with an outside micrometer. Thus it was possible to determine the preload in the bolt.

Results of the Preload Test

Figure 2 shows the results from the tightening tests with the nominal preload of \( F_y = 510 \text{ kN} \) (70% yield strength [1]). It can be seen that 4 of 15 bolts (conventional assembly tightened with reaction arm) did not reach the required load (test specimen 1-15). For the hot-galvanized DISC only one test specimen did not reach the preload. All tests with boltcoat DISC (201-215) achieved the preload.

The linear relationship between preload and torque moment from the VDI 2230 [2] was used for the determination of the torque moment for the increased preload level. Figure 3 presents the results of the tightening tests with higher preload level. It can be seen that the conventional tightened test specimen did not reach the required preloads in 9 of 15 cases. On the contrary only one test specimen of the DISC-equipped specimen did not reach the minimum threshold value respectively. Four test specimen equipped with DISC have been tightened beyond the plastic limit. It has to be mentioned that this is not acceptable for dynamic loaded connections.

Statistical Evaluation

In addition to the measurements a statistical evaluation was carried out. At first mavericks were detected and eliminated. Afterwards the standardised normal distributions for the two different load levels and three different bolt assemblies were calculated (see Fig. 4 and Fig. 5). It can be seen that the application of the DISC reduces the preload scatter significantly. Especially on the nominal preload level.
the scatter could be reduced from 12% to 4% (assembly with hot-galvanized DISC). This tendency can also be seen for the increased load level. The preload scatter was reduced from 16% to 5% (assembly with DISC with boltcoat surface finish).

Conclusion

Within this ForWind development project 90 bolts M36 were tested on two different preload levels and three different assemblies. Besides the conventional bolt assembly with torque tool with reaction arm the DISC assembly without reaction arm was tested. The influence of the DISC regarding the preload and friction scatter was investigated. In some cases the achieved preload level was higher than the plastic limit, which is not allowed for the design of connections exposed to high frequent dynamic loading. Using the DISC it was possible to reduce the necessary torque and preload scatter significantly. Thus an increase of the preload level was possible.

Acknowledgment

The ForWind – Center for Wind Energy Research for the financial support and the partners from HYTORC – Barbarino & Kilp, Munich are kindly acknowledged.
References

[1] DIN 18800-7: Steel Structures – Part 7, Execution and constructor’s qualification, Deutsches Institut für Normung e.V., September 2002, Beuth Verlag Berlin

3.1.3 Harmonic Behavior and Thermal Load in the Rotor Winding of Doubly-Fed Induction Generators for Wind Turbines (DP3) (E3-07)

Leibniz Universität Hannover, Institute for Drive Systems and Power Electronics
Sebastian Tegeler, Rainer Helmer, Bernd Ponick
Partner: LÖHER GmbH, Ruhstorf, Rott
Duration: 06.2007 – 05.2008

Introduction

Doubly-fed induction generators are used in large quantities for wind energy applications. For a speed setting range of 1:2, this generator concept (see Fig. 1) just requires a third of the rated power as converter power. The different load points are predicted for these generators by using the T equivalent circuit diagram considering the nonlinear magnetizing reactance. Within the first part of this project, a method was developed to allow a more precise prediction of the magnetizing demand of doubly-fed machines [1] and [2]. This method is given in the ForWind annual report 2007 [3], where the interim results of this project are presented.

The scope of the second part of this project is to investigate the harmonic behavior of stator and rotor voltages and currents. If the amplitudes of the harmonics are high, it is necessary to take them into account in the T equivalent circuit diagram. Furthermore, high harmonics affect the thermal load of the machine.

Approach / Activities

During the second period of this project, substantial measurements at the test field of Loher in Ruhstorf have been made. For these measurements, a 4-pole 1.5 MW generator was tested. The grid for the generator was provided by a 5 MW synchronous machine in order to have a low harmonic behavior. During the measurements, 50 load points from \( \cos \varphi = 0.3 \) to \( \cos \varphi = 1 \) were logged. Later all load points were analyzed and compared with the data collected by the measurement system of Loher. The system of Loher only collects the rms values of voltages and currents, so that it was necessary to take these measurements in the test field and analyze the harmonic behavior of the generator. The specified measurement categories are displayed in Figure 1.

The harmonic behavior of the different load points is quite the same. For example the Fourier analysis of one load point according to the specified measurement categories is given in this report. The FFT diagram for the rotor signals is shown in Figure 2. The main values of this load point are given in Table 1.

![Figure 1: Doubly-Fed Induction Generator Concept](image1)

![Figure 2: Fourier analysis of the rotor values](image2)

<table>
<thead>
<tr>
<th>n in rpm</th>
<th>f in Hz</th>
<th>U in V</th>
<th>P in kW</th>
<th>Q in kVar</th>
<th>P2 in kW</th>
<th>I1 in A</th>
<th>I2 in A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1799</td>
<td>50</td>
<td>690.0</td>
<td>1277.3</td>
<td>655.6</td>
<td>242.0</td>
<td>1201.3</td>
<td>414.7</td>
</tr>
</tbody>
</table>

Table 1: Main values of the load point
At the first step rotor values are analyzed, because due to the converter in the rotor circuit, the harmonic behavior is supposed to be higher than in the stator circuit. The Fourier analysis of the rotor values is shown in Figure 2. The values in this diagram are to be understood as amplitude values of the individual frequencies. Here the 2 kHz pulse frequency of the converter as well as multiples of the converter pulse frequency are clearly visible. The rms value of the rotor voltage in this load point is 357.8 V. The largest harmonic amplitude compared to the fundamental of the voltage is about 22%.

In the Fourier analysis of the rotor current, the same frequencies can be found as in the rotor voltage. The amplitude of the pulse frequency at 2 kHz compared to the amplitude of the fundamental of the current is about 0.77%. Therefore, the impact of the harmonic behavior in the rotor circuit is negligible. The rms value of the rotor current in this load point is 414.7A and can be predicted with an accuracy of 0.5% by using the method that was developed during the first period of this project.

Performing a Fourier analysis of the stator and rotor current close to the pulse frequency, the main harmonic amplitudes in the rotor current can be calculated as follows:

\[ f_x = f_{\text{pulse}} \pm 2 \cdot f_2. \]

The fundamental wave slip frequency of the rotor current is about 10 Hz according to the speed of 1799 rpm. Both of these components at 1980 Hz and 2020 Hz are generating a field in the air gap of the generator which induces a voltage in the stator winding with the following frequency:

\[ f_{x1} = p \cdot n \pm f_{x2} \]

The harmonic amplitude of the 2 kHz component in the stator current is, related to the amplitude of the fundamental, about 0.64% and in the stator voltage 0.25%. Therefore, the impact of the harmonic behavior of this generator is negligible.

**Results**

The impact of the harmonic behavior of the stator and rotor current is very low, thus it does not affect the operation behavior of the generator in a significant way. Therefore, it is not necessary to implement the different harmonics into the T equivalent circuit diagram, and no significant additional thermal load is caused by the harmonics of the converter in the rotor circuit.

With the method developed in this project, an accuracy predicting the rotor current of less than 2.5% is possible. Therefore, the project partner is also able to make better predictions for the thermal load in the rotor winding.

**References**

3.1.4 Development Project
ForWind-Academy: A Unique Offer for Academics to Obtain Qualification (E1-08)

ForWind Competence Center
Stephan Barth, Nicole Kadagies, Moses Kärn
Partner: Overspeed GmbH & Co. KG
Duration: 06.2008 – 03.2009

Description
The ForWind Academy development project was launched in June 2008. A partner in this project is Dr. Hans-Peter Waldl, general manager of Overspeed GmbH & Co. KG, drawing on over 20 years of branch expertise as a consultant and instructor. Together with Overspeed GmbH & Co. KG, ForWind goes by the name ForWind Academy and initiates the offering of high-quality seminars and advanced training for academics in the wind energy sector. The target groups are experts and management, decision makers and innovators. Seminars on offer take up current issues occurring in real-world field scenarios and present interfaces to scientific knowledge gained from research and development. The ForWind Academy development project is particularly adept when it comes to level of expertise and the didactic preparation of seminar topics and content.

What ForWind Academy offers sets it apart from the available mass of training possibilities which generally tend to serve as an introduction by conveying basic knowledge with no direct link to current topics in research and development. Furthermore, lecturers are not merely selected by expertise, but also by their experience as teachers.

The ForWind Academy was preceded by the excellent cooperation between ForWind and Overspeed GmbH & Co. KG which exists as part of the unique and innovative program: “Continuing Studies Program in Wind Energy Technology and Management”.

Approach / Activities
In the last few years the wind energy branch has been experiencing rapid growth, making it an important area for future development and offering manufacturers, subcontractors and service providers’ significant potential for future growth. At the same time, the wind energy sector is suffering from a lack of highly skilled personnel, and this situation is aggravated by the absence of structured and specialized academic training programs as well as courses, such as what is the norm in the automobile and aircraft industry. During the starting phase of the sector’s growth it was possible to train people on the job. However, currently the tasks and demand for experts have reached a level which makes pre-existing qualifications essential. As a result, the successful development of the wind energy sector will be increasingly tied to the availability of courses like those which the ForWind Academy offers, along with training and professional certification opportunities.

The partners ForWind and Overspeed GmbH & Co. KG began by compiling a range of topics in the areas of management, planning and engineering which are highly relevant to the wind energy sector. This initial concept for content was followed by direct talks with the experts and co-contributors involved. At the same time, a marketing concept was prepared and conducted to reach out to the target groups involved in a subject-specific manner. The two first seminars took place in November 2008 with a total of 20 participants. On account of the marketing activities and the high profile following as a result, the actors involved in the current 2009 seminar program are looking forward to a higher number of participants.

Focusing on the new EEG 2009, the first one-day seminar was held on 19 November 2008 by the attorney Dr. Jan Reshöft from Kanzlei Berghaus und Partner, lecturing on the question “Changes and Potential: What Will the New EEG 2009 Feature?” Three co-lecturers assisted this seminar concept.

The main focus of the 2nd seminar on 25 and 26 November 2008 was “Grid Connection Features of Wind Energy Facilities” with Prof. Dr. Detlef Schulz from the Helmut-Schmidt-University Hamburg. The ForWind Academy offers a platform for intensive advanced training and the exchange of ideas. Seminars shall furthermore be accessible to newcomers looking to acquaint themselves with a specific topic and for contact to specialists. Apart from advanced training, the ForWind Academy also serves in the creation and support of networks.

Results
ForWind Academy will continue to establish its reputation as the place to look when it comes to high-class seminars dealing with current topics on an academic level and with a high degree of relevance to practical applications, also functioning as a communication exchange among experts. In doing so, ForWind Academy extends the range of services provided by ForWind and contributes to its own name as a place for conducting wind energy research and the knowledge transfer. In 2008 ForWind Academy successfully began its activities with two seminar events. In the first six months of 2009, the offer shall comprise a total of 9 seminar events. In addition to the seminars on offer, we will be placing emphasis on the compilation and extension of in-house seminars for companies with specific problems to be addressed.

Next Steps
– Execution of the current seminars on offer for the first half-year of 2009

Further information about the ForWind Academy, the seminars on offer and its partners are provided at:
www.forwind-academy.com
3.1.5 Analysis of Unsteady Flow on Rotating Wind Turbine Blades (E2-08)

Carl von Ossietzky Universität Oldenburg
Institute of Physics
Bernhard Stoevesandt, Nils Kirrkamm, Joachim Peinke
Partners: REpower Systems AG
Duration: 10.2008 – 03.2009

Motivation

On blades of wind turbines a lot of vortex separation appears preferably at the blade root. This is caused by the nacelle, the tower and mainly by the special geometry of the blade at the root. Such vortices are forced towards the outer blade by the Coriolis-force. This leads to unsteady effects on the blade causing mechanical loads.

The research on such effects appears to be rather difficult, as the effect is unsteady and due to the rotational domain hard to reach experimentally. Research has so far been done using wind tunnel measurements [1] and steady computational Reynolds averaged numerical simulations [2]. Both methods had difficulties to show the real characteristics of the unsteady flow along the blade.

Therefore we aim to improve the numerical simulation to also resolve the unsteady effects on the blade. Time resolves simulations especially of the critical regions are to be done and the results to be evaluated especially with stochastic analysis. The obtained data is to be used for the optimization of the inner part of future blades.

Activities

For an analysis REpower made a 40 m blade of their 2 MW class turbines available. Also REpower constructed a grid and performed a k-e steady state model – state of the art simulation using CFX-ansys as a benchmark.

This was to be met by simulation using OpenFOAM. Nevertheless the Ansys grid did not prove to be suitable for or convertible to OpenFOAM. Therefore a similar grid has been constructed for OpenFOAM and in a first step a comparable k-e steady state simulation was done. Both results are to be compared to a few measurements done by REpower to compare the over all results. In a second step an unsteady simulation has been performed using OpenFOAM.

Outlook

As the Project is still running the evaluation of the results is in progress. As OpenFOAM offers many options and models further improvements will be possible in the future. Also so far the size of the grid has been kept to a limit of 8 million elements. This size is a result of computational limits up to now, set by todays desktop computers, that are used within the companies. Lager grids could of cause improve the simulation quality. The availability of larger computational clusters for wind turbines manufacturers may become therefore a crucial question. Even more as the size of the wind turbine blades increases more and more.

References


3.1.6 Novel Line-side Control Methods for Wind Energy Plants with Medium Voltage Converters (E3-08)

Leibniz Universität Hannover, Institute for Drive Systems and Power Electronics
Michael Wöhrmann, Axel Mertens
Partner: Siemens AG, Nürnberg
Start: 12.2008

Introduction

As an alternative to low voltage converters used so far, medium voltage converters are most suitable to be applied in wind energy plants with synchronous generator and full converter for a power of 3 MW and higher. Advantages are lower current and smaller conductor diameter while producing the same power output. In this way, the nacelle weight and thus the weight of the complete construction can be reduced.

Medium voltage converters only tolerate low switching frequencies less than 1000 Hz, which, when using conventional control methods, lead to considerable output current distortions, thus limiting the control dynamics. This can be improved by increasing the switching frequencies, which on the other hand is accompanied by considerably higher heat losses in the semiconductor elements.

The Institute for Drive Systems and Power Electronics (IAL) has developed a novel control method for converters with LC output filter for controlling electric drives [1], thus enabling dynamic control even with very low switching frequencies. Within the scope of the present ForWind development project, it is investigated if this control method is suitable for the supply into a medium voltage grid. Contrary to the drive control, the grid connected converters have to comply with the standards given by the utility companies [2]. The requirements how to react on line disturbances are above all challenging for the closed-loop control.

Approach / Activities

The control method is a predictive control which IAL has developed so far only for induction machines. The semiconductor valves of the converter are not controlled according to a fixed switching pattern, but it is decided at each switching instant with which switching position the output state required in the next instant can most suitably be reached. For this purpose, all suitable switching states are calculated, with regard to their effect on the output current waveforms and the voltage at the filter capacitor, and then the one with the most favorable resulting behavior is selected.

The investigation of the aforementioned method for the mains supply requires a suitable simulation model, which can roughly be divided into two blocks: Converter model with filter and control and a medium voltage grid model.

For this purpose, the model already existing at IAL must be adapted and modified. First, the output filter has to be designed with respect to the line impedance, so that the resonance frequency is within the range of the switching frequency of about 400 Hz and the filter offers a good resistance towards disturbances and line harmonics. The differential equations of the filter model integrated in the predictive control and of the line model must be changed according to the design, in order to be able to calculate the system behavior for the next particular switching state.

In addition, a line model has to be developed and verified. The model step size must be in the µs range, in order to be able to picture line harmonics and switching operations. For the line model, the attention is also turned on the simulation of possible line disturbances, as for example short circuits near and far away from connecting points.

It must be investigated, if the control method used complies with the connection standards, as for example supply in a short circuit with double rated current for at least 150 ms [2], without exceeding the thresholds at which the converter switches off. It must be determined by means of steady-state simulations if the LCL filter applied is sufficient to comply with the requirements on harmonics being impressed to the mains, or if additional filters must be provided.

References

3.2 Other Projects

3.2.1 GROW – Grouted Connections for Offshore Wind Turbine Structures

Leibniz Universität Hannover, Institute for Steel Construction
Peter Schaumann, Stephan Lochte-Holtgreven
Partners: Germanischer Lloyd Industrial Services GmbH, Hamburg, SIAG Anlagenbau Finsterwalde GmbH, Finsterwalde, Heijmans Oevermann GmbH, Münster
Funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
Duration: 10.2006 – 03.2010

The research project GROW – Grouted Connections for Offshore Wind Turbine Structures – is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), which is represented by the Projekträger Jülich (PTJ). GROW started in October 2006 and will end in March 2010. During this period the bearing behavior of grouted connections of offshore wind turbine support structures is investigated at different limit states. Therefore, several small scale tests have been carried out to investigate the axial force capacity. In addition large scale bending tests are performed at the laboratories in Hanover.

Monopiles with grouted connections will be one type of the support structures in the upcoming German Offshore Wind Projects inside and outside the twelve miles nautical zone. In comparison to other parts of the monopile the grouted connection is a quite expensive detail. A cost reduction of this construction detail becomes more and more decisive in the competition with other support structure solutions.

The conclusions and results of the former ForWind-Project TP V: “Forecast of Fatigue Life of Support Structures of Offshore Wind Energy Conversion Systems” were used as basis for GROW. The test-setup from the ForWind-Project TP V was modified. The test frame will be used for large scale tests with different materials and geometric properties. The overlap length between monopile and transition piece and the material strengths of the used grout mortars will be downscaled significantly.

National and European companies support the research work by providing measurement data, grout materials and design know-how.

3.2.2 Deutscher Windmonitor – German Wind Monitor: Characterization and Prediction of the Wind Field

Carl von Ossietzky Universität Oldenburg
Institute of Physics
Jinhua Jiang, Lüder von Bremen, Detlev Heinemann, Jens Tambke
Partners: ISET e.V., Universität Kassel
Funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
Duration: 2007-2008

For Wind’s task in the project German Wind Monitor (Deutscher Windmonitor) was to provide forecasted wind fields which are corrected with in-situ wind observations from measurement masts. The corrected wind fields are the basis for improved wind power predictions that are important for a safe grid integration of fluctuating wind power. The correction of wind fields is necessary as Numerical Weather Predictions (NWP) may suffer from phase-shifts in forecasts and very local developments like strong depression.

Wind measurements of 2004 and part of 2006, collected in ISET’s WMEP program (Scientific Measurement and Evaluation Program) were used to correct the wind field forecasts of the German Weather
Service's Local Model (DWD-LM, now COSMO-EU). Wind data of met-masts at 44 stations distributed over whole Germany were available. They were measured at two observational levels (10 m and 30 to 50 m, depending on the site). After preprocessing (quality control) of the data, the systematic error (bias), the phase error and the local-scale error were corrected.

The bias correction led to a reduction of the root mean square error (RMSE) by 0.3 m/s to 0.4 m/s at the first observational level, and 0.1 m/s at the second level. The bias matrices were calculated separately for different wind directions.

Another typical prediction error is the phase error. Thus the prediction can be correct in principle but time shifted. A phase correction is applied which compensates these delayed or early wind field predictions. This was realized by an approach which minimizes the error sum of the wind speeds. As result an optimum phase-shift vector was found. The phase correction reduced the RMSE by 0.1 m/s to 0.5 m/s at different time steps (Fig. 1). A second approach, the direct detection of weather fronts, turned out to be very dependent on the data quality.

Local-scale errors are caused by the inadequate representation of local forcing or local weather processes. They were corrected using the observed wind data to derive a correction term. Then the Cressman interpolation technique was used to get a weighted average of correction terms within an influence radius around the grid point. The Cressman scheme was only applied for 30-meter-level wind fields. The correction terms show an underestimation of the wind speed in regions near the North and Baltic Sea, respectively, and in the middle of Germany (Fig. 2), the extent being dependent on the wind direction. Reasons can be the inadequate representation of the land-sea-breeze and the topography. A correction of the local-scale errors decreases the RMSE by 0.1 m/s to 0.2 m/s.

It turned out that phase errors are difficult to capture because weather fronts are not a local phenomenon but depend on the development of a whole weather system and are thus difficult to evaluate correctly. Real-time measurements provide the opportunity to detect and correct these errors considerably. Bias and local-scale errors are much more characteristic for one region. Therefore these errors can be reduced with an evaluation of historic measurements only.

Results show that wind forecasts can benefit from subsequent corrections of systematic, phase and local-scale errors. This is an important requirement that in addition leads to improved wind power predictions.

Figure 1: RMSE of corrected forecasts at 10 m height of 44 stations. Blue points: each station, red lines: all stations. Dashed lines: RMSE of original DWD-LM forecasts for all stations.

Figure 2: Average of correction terms for the wind field over Northern Germany (m/s), data of 2004.
3.2.3 WISENT – Wissensnetz Energiemet eo logie

Carl von Ossietzky Universität Oldenburg, Institute of Physics
Thomas Petrollaigis, Lüder von Bremen, Detlev Heinemann, Jens Tambke
Partners: OFFIS, German Aerospace Center (DLR), Meteocontrol GmbH, University of Oldenburg (EHF), Funded by the Ministry of Education and Research (BMBF), Berlin
Duration: 2006 – 2008

WISENT (Wissensnetz Energiemet eologie) is the German “Knowledge Net Energy Meteorology”. The emphasis is thereby on renewable energies, which depend in particular on the weather situation, and to provide the fundamental concept of energy meteorology.

One of the main work packages focused on the implementation and evaluation of the mesoscale model WRF (Weather Research and Forecasting Model, www.wrf-model.org). A close collaboration with OFFIS that set up the technical infrastructure and operates the computing cluster was established.

WRF’s main components, i.e. preprocessing, solver(s), physics and post-processing modules are shown in Figure 1. WRF is maintained and supported as a community mesoscale model to facilitate wide use in research, particularly in the university community. The WRF software infrastructure supports two dynamical cores, the Advanced Research WRF (ARW), whose development has been led by the National Center for Atmospheric Research (NCAR), and the Non-hydrostatic Mesoscale Model (NMM) core developed by the National Centers for Environmental Prediction (NCEP).

The research goals consisted in improving the wind speed forecasting skill. The technical goals consisted in successfully and efficiently utilizing the heterogeneous computing resources available within D-Grid and in implementing a generally usable, sustainable framework for running the WRF model and post-processing its raw output for the purposes of energy meteorology community (e.g. vertical interpolation to desired height levels, horizontal interpolation to desired coordinates, lag averaging, computing verification scores and so on). Finally, the organizational goals consisted in establishing a set of standardized procedures, tools, and domain knowledge necessary to perform research and to provide semi-operational wind forecasting services, as well as identifying further opportunities for transferring this knowledge into generalized energy meteorology applications (e.g. solar energy).

The research work resulted in the initial implementation and validation of WRF as the mesoscale platform in WISENT, followed by the examination of the Lagged Average Forecasting (LAF) methodology for wind speed prediction, which was later refined by combining LAFs into ensemble schemes using optimal weights. Based on our results, the construction of a Combined Prediction System (CPS) comprising deterministic and ensemble members was possible using an optimal combination of different forecast components such as NCEP GFS deterministic forecasts, NCEP GFS LAFs, WRF deterministic high-resolution (mesoscale) forecasts, and WRF LAFs. This CPS can be extended to include additional components, for example ECMWF IFS deterministic forecasts and ECMWF Ensemble Prediction System (EPS). Such an optimally combined meteorological forecast system (CPS) linked to wind power forecasting tools should be evaluated on all relevant time scales that are interesting to end-users, such as wind farm operators, transmission system operators and energy traders. The technical work resulted in the “gridification” of WRF – establishing the procedures and tools for maintaining model installations and executing instances of the model at multiple D-Grid sites and for data post-processing as required by the Lagged Average Forecasting methodology.

Figure 1: Weather Research and Forecasting Model’s main components
3.2.4 Decentralized Energy Management (DEMS) Project – Wind Power and Load Forecast

Carl von Ossietzky Universität Oldenburg Institute of Physics
Nadja Busch-Saleck, Jethro Betcke, Florian Bertsch, Ulf Gräwe,
Lüder von Bremen, Detlev Heinemann
Partners: FH Wilhelmshaven, TU Clausthal, Leibniz Universität Hannover, OFFIS e.V., BTC AG, EWE AG; Funded by EWE AG
Duration: 2004 – 2008

Introduction

The research project DEMS was initiated to develop a Decentralized Energy Management System (DEMS). Especially renewable energies can be managed effectively in such a system which accounts for the fluctuating energy supply.

ForWind was responsible for wind power and load predictions.

Wind Power Prediction

ForWind runs two wind power prediction models, a physical one (Hugin) and a statistical one, based on Neural Networks. They both use wind speed of Numerical Weather Prediction Models as input data. Their time horizon is up to 72 hours.

The models were adapted for the special needs of the project, with clear focus on Hugin. This means wind power predictions for the EWE region (north-westerly region of Germany) and single wind farms were realized. Fed-in wind power serves as reference data which allows better adaption to real values and error evaluation. Model Output Statistics help to optimize the predictions.

It is shown that the error of the wind power prediction is highly dependent on the size of the predicted area. Error smoothing of independent errors in large areas results in smaller errors.

The statistical model turns out to have lower prediction errors. This is mainly due to the adaptive power curve which considers the different regional conditions. This is an advantage especially for single spots because corresponding prediction errors of the input data are relatively high.

Additional to the deterministic prediction the uncertainty was estimated by an approach based only on the preceding time series of the wind power. Several error measures were defined which characterize the time series. Their combination could then be related to the forecast error. The results show realistic uncertainty ranges.

An improvement of the power prediction of the first few hours is possible if the latest wind power feed-in is available for several wind farms in a larger region. This information can then be used to generate or correct the predictions. First studies show promising results, particularly for time periods of very pronounced weather situations like periods of predominant west wind.

The classification of different weather regimes was realized using atmospheric pressure fields over Europe. Cluster analysis of those data categorized the prevailing weather system of each day.

Conventional wind power predictions base on global numerical weather prediction models. Their precision is limited when predictions for small regions are considered. Since the wind power prediction is highly dependent on these input data, it is recommended to improve the quality of them directly. In following studies this will be realized by mesoscale modeling or ensemble prediction, which is a combination of several weather prediction models.

User Load Prediction

An accurate day-ahead prediction of the electricity demand is essential for both the economical and technical planning of the electricity production and distribution. Until recently the electricity production was highly centralized and it was sufficient to predict the user load only for larger regions, typically the size of a utility grid. These predictions are usually carried out by an experienced expert aided with some computer tools. However, with the growing contribution of decentralized energy production, grid management requires user load predictions for smaller subgrids. The shear number of these subgrids requires automation of the prediction process. To this end ForWind has developed the software package ProLa.
ProLa uses historical data to establish empirical relationships between user load and so-called exogenous parameters, i.e. external factors that influence the user load. These exogenous parameters can be divided in predictable “calendar” quantities such as the hour of day, day of the week and schoolholidays, and weather quantities such as temperature and solar irradiance. It was shown that the user load depends not only on the current weather, but on the weather in the recent past and even on the anticipated weather in the near future. To take this hysteresis effects into account without getting too much free parameters redundancy in weather time series were removed using principle component analysis. The relationships between user load and the principle components of the weather data can than be applied to the weather forecast to obtain a prediction for the user load.

The method described above ignores the presence of trends, such as caused by the gradual increase in the use electrical appliances. To take these long term trends into account the deterministic ProLa approach was combined with a simple autoregression model. This further increased the accuracy of the model.
3.2.5 Joint Research Project “Development of LiDAR Measurement Techniques for the German Offshore Test Site”

Carl von Ossietzky Universität Oldenburg
Institute of Physics
Matthias Wächter, Joachim Peinke
Partners: SWE (Endowed Chair of Wind Energy), Universität Stuttgart, DEWI (Deutsches Windenergie Institut), DLR (Deutsches Zentrum für Luft- und Raumfahrt), FGW (Fördergesellschaft Windenergie), Multibrid GmbH
Duration: 08.2007 – 03.2010

Introduction

Wind field measurement by LiDAR (Light Detection and Ranging) technology becomes more and more important with increasing costs for metmasts on the one hand and the need for better spatial and temporal resolution on the other hand. The LiDAR project aims at developing measurement techniques with direct applications for the measurement of power curve and nacelle-based inflow and wake wind fields. Additionally, research-oriented work is done with regard to wake loading simulation and loading control strategies based on inflow measurements.

Activities

The project is coordinated by the Endowed Chair of Wind Energy (SWE) at the University of Stuttgart, Germany, and is conducted in four work packages: the first work package “LiDAR technology” deals with the specification, acquisition, calibration and adaptation for nacelle-based measurements of a commercial LiDAR system. Work package “Power curve measurement” is dedicated to power curve assessment with ground-based LiDAR using standard statistical methods. Additionally, new methods are applied and further developed to derive the power curve from high frequency measurement data, analyzing the short-time dynamics of the power conversion process. The third work package “Wind field research” aims at the development of wake loading simulation methods for wind turbines and the exploration of loading control strategies. Finally, dissemination of results to the industry takes place in work package 4 “Technology transfer”.

Figure 1: Sketch of the measurement principle of the Leosphere WindCube LiDAR system, which is used in the project.

Figure 2: Test site of the first measurement campaign near Bremerhaven, with Multibrid M5000 wind turbine and 102 m metmast of the University of Stuttgart.

Publications

3.2.6 SCHALL 3 – Design, Testing, Realization and Verification of Low Noise Construction Methods and Noise Reduction Techniques During Construction of Offshore Wind Turbines

Leibniz Universität Hannover, Institute for Structural Analysis (coordination)
Raimund Rolles
Participants: German Wind Energy Institute (DEWI), Wilhelmshaven,
Thomas Neumann,
Institute for Technical and Applied Physics (ITAP), Oldenburg,
Manfred Schultz-von Glahn
Funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
Duration: 12.2007 – 11.2010

This research project is funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). The primary objective is the investigation of low noise construction methods and noise reduction techniques during construction of offshore wind turbines. Especially while pile driving activities, sound pressure levels occur that exceed the limit values given by the Umweltbundesamt (UBA) and permanent hearing damage of marine mammals cannot be excluded.

There are primary and secondary actions to be investigated. Primary actions reduce the noise at the sound origin. These are optimization of the impulse pile driving parameters by lengthening the stroke duration on the one hand and the use of vibration pile drivers on the other hand. Secondary actions reduce the noise during sound propagation. Here are coatings and air bubble curtains the object of research. Furthermore, the sound propagation through the seabed is to be quantified.

Noise reduction techniques will be investigated by use of computational simulations and small scale experimental tests in the laboratory. In order to validate the numerical models, experiments will be arranged on a near shore test pile in the Baltic Sea. The final testing of the sound reduction methods will be performed in large scale offshore tests in cooperation with industrial partners.

Figure 1: Simulation of underwater sound propagation
3.2.7 GIGAWIND alpha ventus – Holistic Design Concept for OWEC Support Structures on the Base of Measurements at the Offshore Test Field “alpha ventus”

Leibniz Universität Hannover, Institute for Structural Analysis (coordination)
Raimund Rolfs, Gerrit Haake, Institute for Steel Construction (deputy coordination)
Peter Schaumann
Franzus Institute for Hydraulic, Waterways and Coastal Engineering
Torsten Schlurmann
Institute for Building Materials
Ludger Lohaus
Institute for Soil Mechanics, Foundation Engineering and Waterpower Engineering
Martin Achmus
Partners: Fraunhofer-Institute for Wind Energy and Energy System Technology (IWES), Bremerhaven,
Holger Huhn,
REpower Systems AG, Hamburg,
Multibrid GmbH, Bremerhaven
Funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
Duration: 03.2008 – 04.2011

Primary objective of the RAVE project GIGAWIND alpha ventus is cost reduction for OWEC support structures (towers, different types of substructures and foundations). This can be divided in designing lighter support structures on the one hand (material cost) and in optimizing the design process on the other hand (personnel cost). Because of the interdisciplinary orientation of the project coverage of all civil engineering problems is intended.

This endeavor primarily requires a holistic view on the design process encompassing the following design aspects: Load modeling – analysis of multidirectional wave loads for the estimation of optimized sea state coefficients and correlation with wind loads. Fatigue – varying influence of manufacturing aspects represented by large safety factors. Corrosion – corrosion protection for offshore steel structures. Monitoring – reliable load monitoring at global and local components of the structure. Scour – development of new scour protection systems and local scour monitoring. Foundation – modeling of the load-carrying behavior of driven offshore piles. Validation – automated validation of general structural models. With the integration of separate computational tools into an easy operable simulation and design package with common interfaces the efforts focusing on the design process will be minimized.

The RAVE initiative covers a big measurement campaign like strain gauges, acceleration sensors or water pressure sensors enabling this outstanding research on support structures.
3.2.8 OGOWin – Optimization of Jacket Foundation Structures for Offshore Wind Turbines Concerning Material Consumption, Assembling Order and Manufacturing Process

Leibniz Universität Hannover, Institute for Structural Analysis
Raimund Rolles, Thomas Pahn
Partners: WeserWind GmbH (coordination), Bundesanstalt für Materialforschung und Prüfung (BAM), Europipe GmbH, Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES), Hochtief Construction AG, REpower Systems AG
Funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)

The size of dynamic loads on offshore wind turbines, which are in detail wind, waves and operating state, is essential for the design of the load carrying structure as well as the foundation. Within the collaboration research project OGOWin the Institute for Structural Analysis (ISD) in Hanover deals with the optimization of an offshore wind turbine foundation due to dynamic forces.

Because offshore wind turbines are planned for water depth up to 40 meters, the collaboration work is geared to a secure and economical design of a so called jacket structure. Therefore an onshore prototype was erected in Bremerhaven. Experiences and results obtained at this structure can be transferred later to offshore sites.

The contribution of ISD to optimization process and economical design is the analysis and assessment of the dynamical behavior of the entire structure. Firstly, with a combination of calculation and measurement of the real world structure a validation of the design basis shall be performed.

For that the real structure will be excited by defined test functions as well as ambient excitation to determine the natural frequencies and natural modes (global and local modes). Afterwards the numerical model can be adapted to the real vibration characteristics by means of the measured values (model updating).

The final step deals with the measurement of the jacket structure under natural loads (e.g. wind, waves, operating state) with the aim to investigate realistic load values. This will be reached by performing inverse calculation using the updated FE-Model. Thus with the help of the known dynamical characteristics of the structure and its measured responses load values can be estimated. Finally the comparison of estimated loads to those taken from the present standards and used for the designing process of the structure can distinguish the potential for optimization. This in particular generates benefit in serial production like it is intended for manufacturing load carrying structures for offshore wind turbines.

Figure 1: REpower 5M with jacket foundation structure
3.2.9 Adaption and Test of an Early Damage Detection- and Load Monitoring System for Glass Fiber Blades of Wind Energy Converters

Leibniz Universität Hannover, Institute for Structural Analysis
Raimund Rolfes, Stephan Zerbst
Partners: REpower Systems AG, Rendsburg (coordination), Hottinger Baldwin Messtechnik GmbH, Darmstadt
Funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
Duration: 01.10.2007-30.09.2010

The research project “Adaption and Test of an Early Damage Detection- and Load Monitoring System for Glass Fiber Blades of Wind Energy Converters” is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), which is represented by the Projektträger Jülich (PTJ).

Started in October 2007 it will be finished in September 2010.

During this period a new approach on early damage detection together with new sensing technology specialized for the use inside rotor blades will be investigated. Therefore, first, FE-simulations will be done to carefully prepare the system for further application. After that real fatigue tests on state of the art blade structures are joined and used for necessary system optimizations. At last sensing technology together with early damage detection- and load monitoring system will be implemented to a blade of a wind energy converter to evidence its quality during operation.

The way of manufacturing state of the art blades still offers several uncertainties where damages can grow. Delaminations of fiber layers or bonding failure are realistic damage scenarios. The goal is to spot these starting damages as early as possible to avoid cost intensive repair. Beyond, the option of a damage detection system combined with a load monitoring system can give input to the future design process of even larger rotor blades. Focusing on offshore wind parks today, there is surely a need for reliably working monitoring systems for blade structures to give respect to a challenging environment.

Figure 1: Determination of dynamic structural response of a rotor blade.
3.2.10 Partner in the EU-Project POWER cluster

ForWind Competence Center
Moses Kärn
Duration: 07.2008 – 06.2011

Description

POWER cluster is an EU-Interreg IVB Program partnership to promote offshore wind energy involving eighteen partners from six European countries in the North Sea region, and builds on an already well developed transnational co-operation network – POWER (Pushing Offshore Wind Energy Regions) – which was funded from 2004 until 2007 by the European Union through the Interreg North Sea Program.

POWER cluster runs until June 2011. The network draws on a huge range of expertise, not only in offshore wind energy, but also in oil and gas and other related marine sectors. POWER cluster will develop comprehensive approaches to meet the strategic challenges of the offshore wind energy industry in the North Sea region.

There are four work packages:

1. Social Acceptance – Communicating the benefits of offshore wind energy to the public
2. Business – Creating a business platform to foster offshore wind energy development in the North Sea region
3. Skills – Adapting and preparing the North Sea region workforce to the needs of offshore wind energy
4. Cluster Development – Developing an offshore wind power cluster in the North Sea region

Approach / Activities

The activities of the University of Oldenburg are coordinated by COAST – Center for Environment and Sustainability Research. ForWind, as one of three cooperating working groups, is active in work package 3 “skills”, and contributes to the development of BSc and MSc modules as well as lifelong learning programs in Offshore Wind Energy.

German partners:

- Bremerhavenische Gesellschaft für Investitionsförderung und Stadtentwicklung mbH
- Senator für Umwelt, Bau, Verkehr und Europa des Landes Bremen
- Hochschule Bremerhaven/fk-wind
- Gewerbliche Lehranstalten Bremerhaven
- Carl von Ossietzky Universität Oldenburg
- Stiftung Offshore-Windenergie, Varel
- Landesregierung Schleswig-Holstein, Ministerium für Wissenschaft, Wirtschaft und Verkehr, Kiel
- Wirtschaftskademie Schleswig-Holstein, Husum

International partners:

- Suffolk County Council, Ipswich (UK)
- East of England Energy Group, Great Yarmouth (UK)
- Northumberland College, Ashington (UK)
- South Denmark European Office, Esbjerg (DK)
- Offshore Center Denmark, Esbjerg (DK)
- Aalborg University, Aalborg (DK)
- TU Delft, Faculty LR, Section Wind Energy, Delft (NL)
- Greater Stavanger, Economic Development, Stavanger (NO)
- Chalmers University of Technology, Göteborg (SE)
- Municipality of Öckerö, Öckerö (SE)

Link

www.power-cluster.net
3.3 Continuing Studies Program Wind Energy Technology and Management

ForWind Competence Center Moses Kärn, Christoph Schwarzer
Partners: Windenergie-Agentur Bremerhaven/Bremen e.V. (WAB),
The City of Oldenburg’s Business Support Program

Description

The development of the Continuing Studies in Wind Energy Technology and Management program is a co-operative project between ForWind and WAB as well as the City of Oldenburg. Numerous partners from research, education, industry, and businesses in the field of wind energy supported the realization of this part-time study program as continuing academic education for professionals.

From the beginning in August 2006, the Wind Energy Technology and Management program had a great demand and courses were fully booked with 24 students. The program’s first class successfully graduated in June 2007. Now the fourth class starts in September 2009 and requests for information already suggest that there will be more applications than student places.

The project is sponsored by EWE AG, GE Energy, Bremer Landesbank, wpd think energy GmbH & Co. KG.

Approach / Activities

The Wind Energy Technology and Management program is a unique and innovative program in Germany. The realization of wind energy projects requires that experts from a variety of different disciplines work closely together. As a result problems do occur in day-to-day work situations specifically because the experts are from different disciplines and branches of industry and yet have to communicate with each other. This innovative program of study is one that addresses exactly such challenges, and furthermore fosters a “know-how-transfer” from acknowledged experts in the field and from universities thus, providing current and expert knowledge.

The program is directed equally to recent graduates, specialists and executive staff in the wind energy sector, as well as those who wish to enter this field. It offers comprehensive systematic understanding of wind energy projects from scientific grounds to technical, legal and economic realization, as well as skills in planning and project management.

The program is especially designed to fit the requirements of professionals. It comprises self organized studying of reading materials, a two-day seminar once every month and ongoing project work in teams. For the duration of the program an eight-person team will work on a complex wind energy project. During this process, questions will arise relevant to all areas of the curriculum and the students will collectively resolve these issues and the project’s tasks. The total duration of the program is eleven months. It is intended to be short but intensive. A certificate will be issued by the University of Oldenburg upon successfully passing of the examinations. The administrators of the Continuing Studies Program in Wind Energy Technology and Management will ensure the existence of an active network of alumni in order for the students to continue to stay in touch with each other, to assist them in the exchange of professional information, and to support further continuing education possibilities. The second alumni event took place in January 16, 2009 and activities will be continued.

ForWind together with WAB organized workshops which inform about qualification needs and possibilities in the wind energy sector. These workshops were presented by the Jobmesse Erneuerbare Energien at Gelsenkirchen and the windecareer at the international trade fair Husum Wind-Energy 2008.
Results

With three fully booked course cycles and a rising demand for the fourth class the program has reached a strong position in the market. Feedback from participants and external experts is highly positive.

The program won 2nd place in the Nord-West Award 2007. With this prize the Bremer Landesbank honors projects that are seen to be positively influencing the identity of the Northwest region. The jury is assembled with influential persons of politics, economy, and culture, the presidency changing between the premiers of the states of Lower Saxony, Christian Wulff, and the Free State of Bremen, Jens Börnsen.

Through its innovative concept and integration of numerous well-known experts from the field the program sets new standards in continuing education, establishing continuing education for experts on an academic level in the region.

Also, it was honored that the program was realized by a cooperation of public and private partners: WAB, the Forschungs- und Koordinierungsstelle Windenergie at the Hochschule Bremerhaven (fk-wind), Stiftungslehrstuhl Windenergie at the University of Stuttgart (SWE), and the Overspeed GmbH & Co. KG.

Next Steps

Start of the fourth class: September 2009 (application deadline June 1st, 2009)

Further information, its contents and partners are provided at:

www.windstudium.de
3.4 Events Hosted by ForWind

ForWind offers a diverse program of events on topics pertaining to all aspects of wind energy.

In seminars and workshops, ForWind tackles current research questions from the wind energy sector. A series of lectures accompanies the semester with national and international speakers, informing a broad-based public about current developments in the area of wind energy. Conventions and symposiums are organized by ForWind of its own accord and as a commissioned organizer. ForWind has been commissioned by, among others, the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (BMU), the Ministry for Science and Culture of Lower Saxony, European Regions as well as the city of Oldenburg.

In 2008 ForWind has hosted various events; examples are described below.

3.4.1 ForWind Course of Lectures

Summer Term 2008 and Winter Term 2008/2009
ForWind Competence Center, Elke Seidel

Since summer term 2006 ForWind organizes a unique public course of lectures concerning different, predominantly technical aspects in the field of energy – mainly focused on wind energy.

This course of lectures is supposed to support the exchange of information. Meant as an interlink between research institutions and the industry, it offers students, employees of the University of Oldenburg, colleagues of other institutes or business companies as well as interested private persons to inform themselves about various subjects and discuss them with invited national and international experts.

To support networking activities ForWind offers a get-together after each talk with cold drinks and snacks. The number of participants in general is growing, as is the number of sponsors - indicating the interest of the industry.

Another service offered by ForWind is the possibility to download further information and the slides of each talk, if made available by the speakers. Flyer and poster promote ForWind and each current course of lectures and are already requested in a remarkable number by sponsors, ministries and other interested institutions.
ForWind Course of Lectures

Lectures Summer Term 2008

Herausforderung Offshore-Windpark
Jens Gößwein,
Geschäftsbereich Offshore,
REpower Systems AG

Zukunft der erneuerbaren Energien – Zukunft Deutschland
Dietmar Schütz,
Bundesverband Erneuerbare Energie e.V.

Elektromobilität aus Sicht eines Energieversorgers
Dr. Jörg Hermsmeier,
EWE AG

Mit Umsicht für Natur und Umwelt – ökologische Begleitforschung im Offshore-Windpark alpha ventus
Christian Dahlke / Kristin Finger,
Bundesamt für Seeschifffahrt und Hydrographie (BSH)
Lectures Winter Term 2008/2009

Die Strategien der Bundesregierung für den Ausbau der Offshore – Windenergie im Lichte der Raumordnungsplanung für die AWZ
Jörg Kuhbier,
Stiftung OFFSHORE-WINDENERGIE

Steuerung von Offshore-Windparks – das integrierte Leitsystem für alpha ventus
Dr. Till Luhmann,
BTC AG

Perspektive Windkraft – wo geht es hin?
Heiko Roß,
Bard Engineering GmbH

Nordsee-Ost: ein Offshore-Projekt in Umsetzung
Dr. Agnieszka Cieplinska,
Essent Wind Deutschland GmbH

Herausforderungen der Zertifizierung von Windenergieanlagen
Christian Nath,
Germanischer Lloyd AG

Die Rolle eines Energieversorgers im Wandel der Energieerzeugung – Norddeutschland und die Windkraft
Dr. Werner Brinker,
EWE AG

Netzintegration von Windenergieanlagen
Prof. Dr. Detlef Schulz,
Helmut-Schmidt-Universität, Hamburg

Klimaänderungen – Ursachen, Wirkungen, Maßnahmen
Prof. Dr. Hartmut Graßl,
Max-Planck-Institut für Meteorologie

The Course of Lectures was sponsored by the following companies:
Bremer Landesbank,
BTC Business Technology Consult AG,
Essent Wind Deutschland GmbH,
EWE AG,
Germanischer Lloyd AG,
Marsh GmbH,
Stiftung Offshore-Windenergie,
Vattenfall Europe New Energy GmbH
3.4.2 RAVE – Research At Alpha Ventus

ForWind Competence Center, Elke Seidel

On May 8th 2008 ForWind organized the Kick-off meeting for RAVE (Research at alpha ventus). The offshore strategy of the federal government is set towards the goal of erecting offshore wind parks with an installed power totalling 20 to 25 gigawatts by the year 2030. This corresponds to a share of approx. 15% of the power consumption in Germany.

The starting signal for this development was set off by the offshore testing range “alpha ventus” which is operated by the large energy providers E.ON, EWE and Vattenfall. With this in mind, they founded the Deutsche Offshore-Testfeld- und Infrastruktur-GmbH & Co. KG (DOTI) which set itself the goal of constructing the first wind turbines on the sea. Alpha ventus is to serve as an initial spark for the utilization of wind energy in the German North and Baltic Sea.

In order for the German wind energy industry to benefit most from this testing range, the Federal Ministry for Environment, Nature Conservation and Nuclear Safety (or BMU with initials from German name) has started a comprehensive research initiative which accompanies the construction and operation in the areas involved. These research activities promoted by the BMU are known under the acronym “RAVE – Research at alpha ventus”. The testing region is equipped with comprehensive measuring technology in order to be able to provide detailed data to all the projects taking part. In 2008, RAVE’s opening event took place at the Representation of Lower Saxony at the Federal Government in Berlin. There, research associations promoted by BMU participating in the testing region along with numerous individual offshore research activities and the current state of construction measures were presented to the general public.
Kick-off Meeting RAVE – Program

Eröffnung und Überblick

Begrüßung
Heiko Gevers, Niedersächsisches Ministerium für Wissenschaft und Kultur
Prof. Dr.-Ing. Jürgen Schmid, ISET e.V.

Eröffnungsvortrag:
**Offshore-Windenergie – ein zentraler Baustein für das 20%-Ziel für erneuerbare Energien**
Michael Müller, Parlamentarischer Staatssekretär im Bundesumweltministerium für Umwelt, Naturschutz und Reaktorsicherheit

Das Testfeld alpha ventus und der Stand der Realisierung
Wilfried Hube, DOTI GmbH & Co. KG

**Offshore: Die MS000 geht an den Start**
Ingo de Buhr, Multibrid GmbH

**REpower 5M – Testfeld, Markteinführung und Serienfertigung**
Dr. Martin Skiba, REpower Systems AG

**RAVE – die Forschungsinitiative zum Testfeld alpha ventus**
Dr. Bernhard Lange, ISET e.V.

Moderation: Prof. Dr.-Ing. Raimund Rolfes
ForWind, Leibniz Universität Hannover

**RAVE – Forschungsschwerpunkte**

**Offshore-Windbedingungen: Der „Rohstoff“ für alpha ventus**
Prof. Dr. Joachim Peinke, ForWind, Universität Oldenburg

**Offshore-Windenergieanlagen: Was sie aushalten, was sie leisten**
Prof. Dr.-Ing. Martin Kühn, Stiftungslehrstuhl Windenergie, Universität Stuttgart

**Tragstrukturen: Fest verankert, langlebig und zugleich wirtschaftlich**
Prof. Dr.-Ing. Raimund Rolfes, Prof. Dr.-Ing. Peter Schaumann, ForWind, Leibniz Universität Hannover

**Wieviel Wind verträgt das Netz – Herausforderungen der Netzintegration**
Dr. Kurt Rohrig, ISET e.V.

**Mit Umsicht für Natur und Umwelt – Ökologische Begleitforschung im Testfeld**
Christian Dahlke, Bundesamt für Seeschifffahrt und Hydrographie

Moderation: Prof. Dr.-Ing. Peter Schaumann
ForWind, Leibniz Universität Hannover

Podiumsdiskussion zu OWMEP und Technologieentwicklung bis 2020

Impuls­vortrag:
**Offshore – Internationale Entwicklungstendenzen**
Jens Peter Molly, DEWI GmbH

Impuls­vortrag:
**OWMEP – das wissenschaftliche Mess- und Evaluierungsprogramm – Offshore**
Prof. Dr.-Ing. Jürgen Schmid, ISET e.V.

Podiumsdiskussion:
**Offshore-Windenergie – Bedeutung eines OWMEP für die Technologieentwicklung bis 2020**
Jens Peter Molly, DEWI GmbH
Prof. Dr.-Ing. Jürgen Schmid, ISET e.V.
Wilfried Hube, DOTI GmbH & Co. KG
Achim Berge, wpd offshore GmbH
Thorsten Herdan, Verband Deutscher Maschinen- und Anlagenbau e. V.
Jörg Kuhbier, Stiftung Offshore-Windenergie

Moderation: Joachim Nick-Leptin,
Bundesumweltministerium für Umwelt, Naturschutz und Reaktorsicherheit
3.4.3 Wakes Measurements and Modeling within and Downwind of Wind farms: Current Features and Future Trends

Workshop, 30 June-2 July 2008, Oldenburg
ForWind Competence Center, Abha Sood

During a scientific workshop, organized by ForWind in Oldenburg, more than 30 experts from industry and research discussed about “Wakes Measurements and Modeling within and downwind of wind farms”. The topic included were in-situ and remote sensing measurements techniques, wake modeling approaches and some case studies followed by a strategic discussion on benchmarking and best practice guideline for wake modeling. An excursion to demonstrate the feasibility of measuring wake turbulence with a Meteorological Micro Aerial Vehicle (MMAV) in a wind park was undertaken.

3.4.4 Science Meets Practice – Innovations for Wind Energy

Conference at HUSUM WindEnergy, 11 September 2008
ForWind Competence Center, Ann-Kathrin Meyer

The „Husum WindEnergy“ is the most important fair for the wind energy sector. Leaders and specialists of the branch come there together. Under the motto “Science Meets Practice”, ForWind invites interested persons from industry, economics and research to the congress center for a one-day conference. Co-operation partner was GE Energy.

The idea: For persistent economic prosperity, the exchange between science and practice is fundamental. Basic research opens the industry new options for action, the contact with companies’ shows scientists where demand is and what succeeds in practice. The concept: Selected pairs of speakers each introduced a topic worked on together from a scientific and practical point of view and discussed this with the plenary assembly. In six sessions, experts from research and industry referred about their topics from two perspectives. More than registered participants listened to the lectures and gave positive feedback to the program.
Science Meets Practice – Innovations for Wind Energy

Welcoming Speech
Prof. Dr. Joachim Peinke, ForWind, Oldenburg

Offshore Wind Energy: Research, Monitoring and Evaluation
– Selected Results of the We®Sea Offshore Wind Energy Research Program
Ir. Jos Beurskens,
Energy research Centre of the Netherlands (ECN), Petten
– 108 MW Offshore Wind Farm Egmond aan Zee: Monitoring and Evaluation Program
Henk Kouwenhoven, Nuon Energy Sourcing, Amsterdam

Wind Flow Modeling and its Impact on Turbines
– Wind Flow Modeling: The Basis for Resource Assessment and Wind Power Forecasting
Dr. Detlev Heinemann, ForWind, Oldenburg
– Wind Turbine Loads – An Application for Atmospheric Flow Modeling
Dipl.-Inf. Carsten Albrecht, AL-PRO GmbH & Co. KG, Großheide

Measure Yaw Misalignment: New Methods and Models
– The Influence of Yawing Error on Performance of Wind Turbines
Prof. Dr. Alois Schaffarczyk, CEwind, Fachhochschule Kiel
– Precise Wind Measurement on Wind Turbines – Pressure and Direction Measurement in front of the Wind Turbine
Dipl.-Ing. Klaus Ritzinger, IXIST Messtechnik GmbH, Rosenheim

Rotor Blades: Challenges for Research and Manufacturing
– Requirements for Today’s Rotor Blades
Prof. Henry Seifert, fk wind, Hochschule Bremerhaven
– Manufacturing of Rotor Blades: New Techniques and Material Systems
Dr. Christoph Wolters, GE Wind Energy GmbH, Salzbergen

Transverse Flux Generators – New Developments for Wind Energy
– Transverse Flux Generators – Principle and Operation Behavior
Prof. Dr.-Ing. Bernd Orlik, Universität Bremen
– Transverse Flux Generators – High Torque, Light Weight
Dr. Norbert Götschmann, Lloyd Dynamowerke GmbH & Co. KG, Bremen

Drive Train: Simulation Tools and Product Development
– Sophisticated Simulation Tools for the Investigation of Roller Bearings to Improve the Reliability of Wind Turbine Gears
Prof. Dr.-Ing. Bernd Sauer, Technische Universität Kaiserslautern
– Modern Product Development of Wind Turbine Drive Train
Dr. Ralf Hambrecht, REpower Systems AG, Rendsburg

Summary
Prof. Dr.-Ing. Peter Schaumann, ForWind, Hanover
4. Documentation

4.1. Publication List

4.1.1 Reviewed Articles


Sušelj, K.; Sood, A.; Heinemann, D.: North Sea near Surface Wind Climate and its Relation to the Large Scale. Submitted to Theoretical and Applied Climatology, (accepted 2009)


4.1.2 Reviewed Conference Contributions

Abdel-Rahman, K.; Achmus, M.: Numerical Investigations of the Effect the Recent Load History on the Behaviour of Steel Piles under Horizontal Loading, 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG). Goa, India, 1-6 October 2008


4.2. Conference List
Bertsch, F.; Saleck, N.; Tambke, J.:  
**Time Series Based Wind Power Forecasts for Crossing Weather Fronts,**  

Gottschall, J.; Peinke, J.:  
**Power Curves for Wind Turbines – a Dynamical Approach,**  

Grünberg, J.; Lohaus, L.; Wefer, M.; Ertel, Ch.:  
**Multi-Axial and Fatigue Behaviour of Ultra-High-Performance Concrete (UHPC),**  
Proceedings of the 2nd International Symposium on Ultra-High Performance Concrete, Kassel, 05.-07.03.2008

Haake, G.; Rolfe, R.; Schaumann, P.; Huhn, H.; Schlurmann, T.; Lohaus, L.; Achmus, M.:  
**Research on Support Structures in the German Offshore Wind Farm alpha ventus,**  

Heinemann, D.; Sood, A.; Sušelj, K.:  
**Integrated Methodology for Offshore Wind Resource and Site Assessment: Wind Distribution and Extremes at Short and Long Time Scales,**  
Poster at European Wind Energy Conference (EWEC), Brussels, Belgium, 30 Mar.-3 Apr. 2008

Heißelmann H.; Hölling, M.; Peinke, J.:  
**Dynamic Behaviour of the Sphere Anemometer,**  
Oral presentation and paper at German Wind Energy Conference (DEWEK). Bremen, Germany, 26-27 Nov. 2008

Jiang, J.; Heinemann D.; von Bremen, L.; Wessel, A.:  
**Evaluation of Wind Field Forecast of DWD-LM Model with Meteorological Mast Observation,**  

**Phase-shift Correction of Wind Field Forecast with Met-mast Observations for Wind Power Forecasting,**  

Klose, M.; Faber, T.; Schaumann, P.; Lochte-Holtgreven, S.:  
**Grouted Connections for Offshore Wind Turbines,**  

Kosel, T.; Kuhlemeier, M.; Zielke, W.:  
**Application of Load Generator Wave Loads 2.0 in OWEC Simulation Frameworks,**  

Kossel, T.; Kuhlemeier, M.; Zielke, W.:  
**Sea State and Wave Load Modeling in WaveLoad 2.0 and its Application in a Multibody Simulation Frameworks,**  

Kühn, M.; Böker, C. et al.:  
**Joint Technology Development for Offshore Wind Turbines – The OWEA Project at "alpha ventus",**  
Proceedings of the DEWEK. Bremen, Germany (2008)

Kuo, Y.-S.; Achmus, M.:  
**A Numerical Model to Simulate the Performance of Foundation Elements under Cyclic Load,**  

Lang, B.:  
**Wave and Offshore Wind Resource Characterization,**  

Lippens, V.; Nagel V.; Gottschall J.; Peinke, J.:  
**Performance of Balance: General Motor Ability or Specific Adaptation of Strategies?**  

Lohaus, L.; Anders, S.:  
**Hybride Bauweisen mit Hochleistungsbeton – Neue Chancen aus der Forschung an Grouted Joints,**  
52. Ulmer Betontagung, Neu-Ulm, 12.-14.02.2008

Peinke, J.; Anahua E.; Barth, S.; Gontier, H.; Schaffarzky, A. P.; Kleinhans, D.; Friedrich, R.:  
**Turbulence a Challenging Issue for the Wind Energy Conversion,**  
EWEC Proceedings 2008

**Wind Power Prediction Utilizing Lagged Average Forecasting (LAF) Components from the German D-Grid WISENT's WRF (Weather Research & Forecasting) Model,**  

**Wind Power Prediction Utilizing WRF (Weather Research & Forecasting) Model with Lagged Average Forecasts,**  

Peinke, J.; Anahua E.; Barth, S.; Gontier, H.; Schaffarzky, A. P.; Kleinhans, D.; Friedrich, R.:  
**Turbulence a Challenging Issue for the Wind Energy Conversion,**  
EWEC Proceedings 2008

**Wind Power Prediction Utilizing WRF (Weather Research & Forecasting) Model with Lagged Average Forecasts,**  
Poster at International Supercomputing Conference (ISC). Dresden, Germany, 17 - 20 June 2008

Petroliagis, T. I.; Tambke, J.; Hagedorn, R.:  
**Optimized Ensemble Forecast Schemes Applied to Wind Power Prediction – an Introduction to the EU Project: Safewind,**  
Oral presentation and paper at German Wind Energy Conference (DEWEK). Bremen, Germany, 26-27 Nov. 2008


4.1.4 Lectures at Universities


4.1.5 Project Reports

Jiang, J.: Final Report for Deutscher Windmonitor TP2.2: Characterization and Prediction of the Wind Field

Petroliagis, T. I.; Ploski, J.: Final Report for WISENT Project. Mesoskalige Modellierung (Arbeitspaket 5.2)

4.2 Diploma, Master and Bachelor Theses

Adhikari, S.:
Modellierung des Tragverhaltens von Offshore-Tripod-Gründungen

Apolo Maza, J.:
Untersuchungen zum Kerbdehnungskonzept für Schrauben mit großem Durchmesser

Bimala, A.:
Numerische Untersuchungen zum Tragverhalten vertikal zyklisch Zugpfählen

Castro, F.:
Entwurf und Bemessung von Offshore-Gründungen unter besonderer Berücksichtigung zyklischer Belastungen

Ding, S.:
Untersuchung einer Übergangskonstruktion für eine Windenergieanlage in Hybridbauweise

Dubois, J.:
Untersuchung zur lokalen Dynamik an stählernen Tragstrukturen für Offshore-Windenergieanlagen

Engelke, N.:
Zur Stabilität hybrider Verbindungen in Gründungsstrukturen von Offshore-Windenergieanlagen

Forgoso, P.:
3-D numerische Modellierung von Pfählen unter horizontaler Belastung mit verschiedenen Einwirkungsrichtungen

Gerdener, A.:
Statische und dynamische Bemessung eines Jackets für eine Offshore-Windenergieanlage der 5-MW-Klasse im Testfeld alpha ventus

Gottschalk, M.:
Einfluss der Rissbildung spröder Groutmaterialien auf die Tragfähigkeit biegebeanspruchter Grouted-Joint-Verbindungen für Offshore-Windenergieanlagen

Heißenmann, H.:
Optimierung des Kugelanemometers für die Messung zweidimensionaler Strömungen

Heuer, B.:
3-D numerische Modellierung von Pfählen unter horizontaler Belastung mit verschiedenen Einwirkungsrichtungen

Janke, S.:
Numerische Berechnung des Tragverhaltens von Offshore-Tripod-Gründungen

Klaiber, T.:
Numerische Simulation der Gefügekinetik und des Eigenspannungsfeldes bei MAG-Schweißungen mit normal- und höherfesten Stählen

Knorr, H.:
Tragverhalten und Bemessung vertikal zyklisch belasteter Pfähle

Krebs, M.:
Numerische Berechnung von zyklisch belasteten Fundamenten unter Berücksichtigung des Porenwasserdrucks

Lübbehüsen, A.M.:
Untersuchungen zum gekoppelten Anlagenverhalten von OWEA

Meessen, M.:
Aufbau eines Particle Image Velocimetry-Systems unter Verwendung einer Hochgeschwindigkeitskamera

Mohamed, D.:
Entwurf und Bemessung von Gründungen von Offshore-Windenergieanlagen

Ribiero F.P.:
Berechnung des Tragverhaltens von Gründungen für Onshore Windenergieanlagen

Shaheen, F.:
Tragverhalten vertikal zyklisch belasteter Pfähle

Von Oesen, C.:
Untersuchung einer Grouted-Joint-Verbindung für Offshore-Windenergieanlagen mit massiver Schwergewichtsgründung

Weicken, H.:
Mineralischer Korrosionsschutz für Offshore-Windenergieanlagen

Xiao, Y.:
Entwurf und Bemessung von Offshore-Gründungen

Yang, W.:
Vereinfachte Ermittlung von dimensionsierenden Schnittgrößen für Tragstrukturen für Offshore-Windenergieanlagen

Zachee, M.:
Numerische Untersuchungen von vertikalen Pfählen unter kombinierter Belastung
4.3 PhD Theses

Göthel, O.:
Numerical Modelling of Flow and Wave Induced Scour around Vertical Circular Piles
PhD Thesis,
Leibniz Universität Hannover (2008)

Hölling, M.:
Sensorentwicklung für Turbulenzmessungen
PhD Thesis,
Carl von Ossietzky Universität Oldenburg (2008)

Schimmels, S.:
Numerical Simulation of the Influence of Circular Cylinders on Mixing and Entrainment in Natural Density Currents
PhD Thesis,
Leibniz Universität Hannover (2008)

Wessel, A.:
Entwicklung eines physikalischen Modells der Windpark generierten Turbulenz
PhD Thesis,
Carl von Ossietzky Universität Oldenburg (2008)

4.4 List of ForWind Staff Members

Abdel-Rahman, Khalid, Dr.-Ing.
Institute of Soil Mechanics, Foundation Engineering and Waterpower Engineering
+49 511 762-2273
khalid@igbe.uni-hannover.de

Achmus, Martin, Prof. Dr.-Ing.
Institute of Soil Mechanics, Foundation Engineering and Waterpower Engineering
+49 511 762-4155
achmus@igbe.uni-hannover.de

Barth, Stephan, Dr.
Managing Director
ForWind Competence Center
+49 441 36116-721
stephan.barth@forwind.de

Battermann, Dagmar
ForWind Competence Center
+49 441 36116-720
dagmar.battermann@forwind.de

Bertsch, Florian, Cand.-Inform.
Institute of Physics – Energy Meteorology

Betcke, Jethro, M.Sc.
Institute of Physics – Energy Meteorology
+49 441 36116-736
jethro.betcke@forwind.de

Böker, Cord, Dipl.-Ing.
Institute for Steel Construction
+49 511 762-2492
boeker@stahl.uni-hannover.de

Busch-Saleck, Nadja, Dr.
Institute of Physics – Energy Meteorology
+49 441 36116-733
nadja.saleck@forwind.de

Clausing, Beate
Secretariat
ForWind Competence Center
+49 441 36116-720
beate.clausing@forwind.de

Dapperheld, Jörg
Institute of Physics – Hydromechanics and Wind Energy
+49 441 798-3509
jorg.dapperheld@uni-oldenburg.de

Drews, Anja, Dipl.-Geogr.
Institute of Physics – Energy Meteorology
+49 441 798-3929
anja.drews@uni-oldenburg.de

Gottschall, Julia, M.Sc.
Institute of Physics – Hydromechanics and Wind Energy
+49 441 798-3992
julia.gottschall@forwind.de

Grießmann, Tanja, Dipl.-Ing.
Institute for Structural Analysis
+49 511 762-2247
t.griebmann@isd.uni-hannover.de

Grünenberg, Jürgen, Univ.-Prof. Dr.-Ing.
Institute of Concrete Construction
+49 511 762-3351
gruenberg@ifma.uni-hannover.de

Güker, Gerd, Dr.
Institute of Physics – Hydromechanics and Wind Energy
+49 441 798-3511
gerd.guelker@uni-oldenburg.de

Heinemann, Detlev, Dr.
Institute of Physics – Energy Meteorology
+49 441 798-3543
detlev.heinemann@forwind.de

Helmer, Rainer, Dipl.-Ing.
Institute for Drive Systems and Power Electronics
+49 511 762-2862
helmer@ial.uni-hannover.de
Seidel, Elke
Lectures & Events
ForWind Competence Centre
+49 441 36116-737
elke.seidel@forwind.de

Siebert, Markus, Dipl.-Ing.
Institute of Electric Power Systems
+49 511 762-2807
siebert@iee.uni-hannover.de

Sood, Abha, Dr.
Institute of Physics – Energy Meteorology
+49 441 36116-732
abha.sood@forwind.de

Steinfeld, Gerald, Dr.
Institute of Physics – Hydrodynamics and Wind Energy,
Institute of Physics – Energy Meteorology
+49 441 36116-732
gerald.steinfeld@forwind.de

Steppeler, Stefanie, Dipl.-Ing.
Institute for Steel Construction
+49 511 762-17212
steppeler@stahl.uni-hannover.de

Stoevesandt, Bernhard, Dipl.-Phys.
Institute of Physics – Hydrodynamics and Wind Energy
+49 441 798-3577
bernhard.stoevesandt@forwind.de

Stresing, Robert, Dipl.-Phys.
Institute of Physics – Hydrodynamics and Wind Energy
+49 441 798-3577
robert.stresing@uni-oldenburg.de

Suselj, Kay, M.Sc.
Institute of Physics – Energy Meteorology
+49 441 36116-732
kay.suselj@forwind.de

Tambke, Jens, Dipl.-Phys.
Institute of Physics – Energy Meteorology
+49 441 36116-734
jens.tambke@forwind.de

Tegeler, Sebastian, Dipl.-Ing.
Institute for Drive Systems and Power Electronics
+49 511 762-3758
tegeler@ial.uni-hannover.de

Tipping, Melanie
Team Assistant Professional Training and Further Education
ForWind Competence Center
+49 441 36116-723
melanie.tipping@forwind.de

Wächter, Matthias, Dr.
Institute of Physics – Hydrodynamics and Wind Energy
+49 441 798-3894
matthias.waechter@forwind.de

Wefer, Maik, Dipl.-Ing.
Institute of Building Materials
+49 511 762-3477
maik.wefer@baustoff.uni-hannover.de

Wöhrmann, Michael, Dipl.-Ing.
Institute for Drive Systems and Power Electronics
+49 511 762-3770
woehrmann@ial.uni-hannover.de

Wolff, Miriam, BSc.
Institute of Physics – Energy Meteorology
+49 441 36116-733
miriam.wolff@forwind.de

Wolken-Möhlmann, Gerrit, Dipl.-Phys.
Institute of Physics – Hydrodynamics and Wind Energy
+49 441 798-3894
gerrit.wolken-moehlmann@forwind.de

Zerbst, Stephan, Dipl.-Ing.
Institute for Structural Analysis
+49 511 762-8674
s.zerbst@isd.uni-hannover