INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

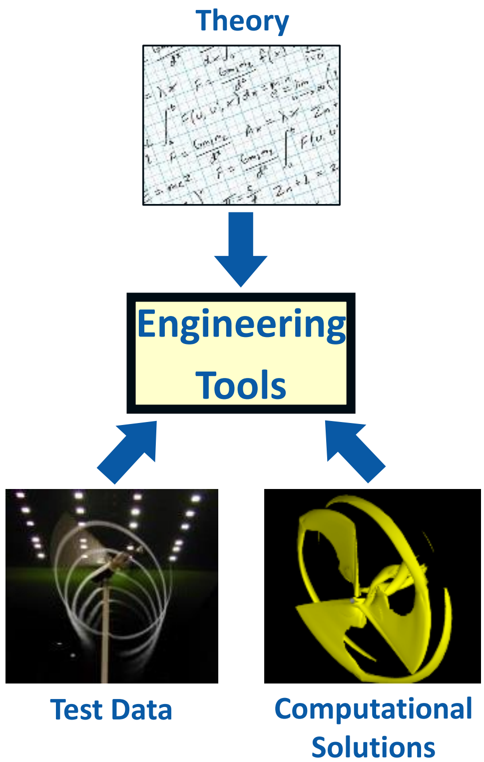
Topical Expert Meeting #88 on

Three-Way Verification and Validation between Data, High-Fidelity Models and Engineering Models

IEA Wind Task 11- Topical expert meeting

September 6-8, 2017

Edinburgh Training and Conference Venue, UK



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International Energy Agency
Implement Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems (IEA Wind)

The IEA international collaboration on energy technology and RD&D is organized under the legal structure of Implementing Agreements, in which Governments, or their delegated agents, participate as Contracting Parties and undertake Tasks identified in specific Annexes.

The IEA's Wind Implementing Agreement began in 1977, and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 26 contracting parties from 22 countries, the European Commission, and Wind Europe, participate in IEA Wind. Austria, Belgium, Canada, Denmark, the European Commission, EWEA, France, Finland, Germany, Greece, Ireland, Italy (two contracting parties), Japan, Republic of China, Republic of Korea, Mexico, Netherlands, Norway (two contracting parties), Portugal, Spain, Sweden, Switzerland, United Kingdom and the United States are now members.

The development and maturing of wind energy technology over the past 30 years has been facilitated through vigorous national programs of research, development, demonstration, and financial incentives. In this process, IEA Wind has played a role by providing a flexible framework for cost-effective joint research projects and information exchange.

The mission of the IEA Wind Agreement continues to be to encourage and support the technological development and global deployment of wind energy technology. To do this, the contracting parties exchange information on their continuing and planned activities and participate in IEA Wind Tasks regarding cooperative research, development, and demonstration of wind systems.

Task 11 of the IEA Wind Agreement, Base Technology Information Exchange, has the objective to promote and disseminate knowledge through cooperative activities and information exchange on R&D topics of common interest to the Task members. These cooperative activities have been part of the Wind Implementing Agreement since 1978.

Task 11 is an important instrument of IEA Wind. It can react flexibly on new technical and scientific developments and information needs. It brings the latest knowledge to wind energy players in the member countries and collects information and recommendations for the work of the IEA Wind Agreement. Task 11 is also an important catalyst for starting new tasks within IEA Wind.

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

The objective of this Task is to promote disseminating knowledge through cooperative activities and information exchange on R&D topics of common interest. Four meetings on different topics are arranged every year, gathering active researchers and experts. These cooperative activities have been part of the Agreement since 1978.

Carballeira Wind Farm - Spain

Two Subtasks

The task includes two subtasks.

The objective of the first subtask is to develop recommended practices (RP). In 2013 were edited RPs on "Social Acceptance of Wind Energy Projects", "Wind Integration Studies" and. "Ground-Based Vertically Profiling Remote Sensing for Wind Resource Assessment".

The objective of the second subtask is to conduct topical expert meetings in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates topics in research areas of current interest, which requires an exchange of information. So far, Topical Expert Meetings are arranged four times a year.

Documentation

Since these activities were initiated in 1978, more than 70 volumes of proceedings have been published. In the series of Recommended Practices 16 documents were published and five of these have revised editions.

All documents produced under Task 11 and published by the Operating Agent are available to citizens of member countries participating in this Task.

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COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
COUNTRY	**INSTITUTION**
Denmark	Danish Technical University (DTU) - Riso National Laboratory
Finland	Technical Research Centre of Finland - VTT Energy
Germany	Bundesministerium fur Umwelt, Naturschutz und Reaktorsicherheit -BMU
Ireland	Sustainable Energy Ireland - SEI
Italy	Ricerca sul sistema energetico, (RSE S.p.A.)
Japan	National Institute of Advanced Industrial Science and Technology AIST
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	Rijksdient voor Ondernemend Nederland (RVO)
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Republic of China	Chinese Wind Energy Association (CWEA)
Spain	Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas CIEMAT
Sweden	Energimyndigheten - Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	CATAPULT Offshore Renewable Energy
United States	The U.S Department of Energy -DOE

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PRESENTATIONS

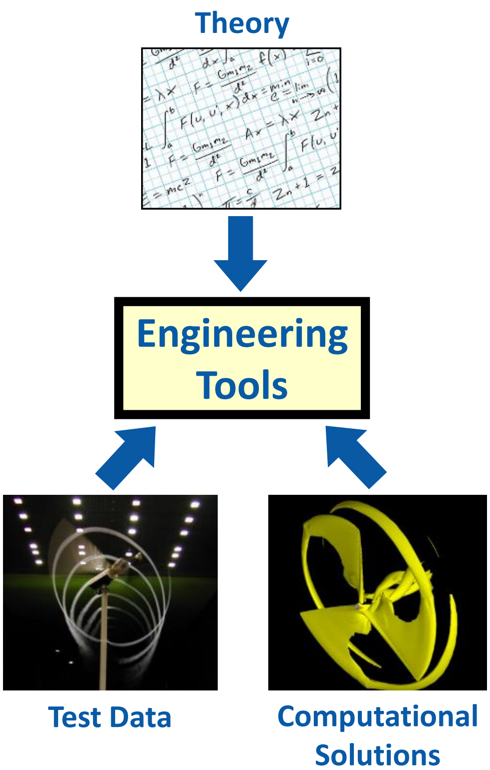
1. INTRODUCTORY NOTE

IEA Wind Task 11 Topical Expert Meeting # 88 on Three-Way Verification and Validation Between Data, High-Fidelity Models, and Engineering Models

Carlos Rodriguez – Offshore Renewable Energy (ORE) Catapult
Jason Jonkman – National Renewable Energy Laboratory (NREL)

BACKGROUND

To support design and analysis—so that wind turbines are innovative, optimized, reliable, and cost-effective—the wind industry and research communities rely on numerical engineering models capable of predicting the coupled dynamic loads and responses of the wind system. Engineering models capture the physical phenomena and system couplings important for the application. While models come in a range of fidelities to target specific problems and are derived from fundamental physical laws, simplifications and assumptions are typically made to ensure the solutions are computationally efficient enough to support the often iterative and probabilistic design process and system optimization. As such, verification and validation (V&V) of the models is key to ensuring accurate solutions.



Verification involves model-to-model comparisons, often confirming the correctness of the numerical implementation, and showing the influence of different modelling approaches. Validation involves comparing numerical model predictions to response data collected experimentally or computationally to ensure the model accurately captures the underlying physics. Computational solutions employing high-fidelity modelling (HFM) are a useful complement to experimental data as properly validated HFM can be used to reliably extract underlying physical phenomena that is difficult to measure experimentally. Uncertainty quantification (UQ) plays a central role in the V&V effort because the assessment of model accuracy is generally made in terms quantification of errors and uncertainties.

But despite V&V efforts to-date, even the most advanced wind energy engineering models are struggling to obtain accurate predictions, especially in the following areas:

- Atmospheric flow and wake and array effect modelling for prediction of wind turbine power performance and loads in wind farms;
- Aero-elastic modelling of modern, large, flexible, and aero-elastically tailored rotors; and
- Hydrodynamic fluid-structure modelling of offshore wind support structures in severe sea states.

The ongoing WakeBench project of IEA Wind Task 31 is working to produce best-practice guidelines for wind farm flow modelling through model intercomparison benchmarks, but little effort has been spent to precisely identify the reasons for modelling discrepancies such that the modelling improvements can be identified. The ongoing Offshore Code Comparison Collaboration, Continued, with Correlation (OC5) project of IEA Wind Task 30 is working to validate offshore wind engineering models, but uncertainty in the experimental data used and lack of HFM solutions has also limited the ability to identify sources of modelling discrepancies and needed improvements. Both of these projects are finishing in the next one-to-two years. Moreover, there is currently no large international collaborative focused on V&V of rotor aero-elastics, despite known prediction discrepancies between the engineering models used in industry and research. There are still pending challenges, including the limited availability of real-scale experimental data, limited availability of validated high-fidelity modelling (HFM) solutions, and limited quantification of model uncertainty for the above areas.

Further V&V of engineering models based on quantitative metrics—along with the associated HFM and experimental data—are needed to ensure model suitability, to classify model limitations and quantify uncertainty, and to identify conditions where further modelling improvements are needed in the future. Hence, we emphasize the need to establish future international collaborative(s) involving three-way V&V between data, HFM, and engineering models in the areas of wind farm aerodynamics, rotor aero-elastics, and offshore hydrodynamics. The recent acquisition by Offshore Renewable Energy (ORE) Catapult of the Levenmouth 7-MW demonstration wind turbine from Samsung Heavy Industries may make it possible to publicly share data from a modern aero-elastically tailored rotor to support a future V&V collaborative.

OBJECTIVES

ORE Catapult and the National Renewable Energy Laboratory (NREL) jointly proposed an IEA Wind Task 11 Topical Expert Meeting (TEM) on three-way V&V between data, HFM, and engineering models in the areas of wind farm aerodynamics, rotor aero-elastics, and offshore hydrodynamics. This meeting will bring together representatives from OC5, WakeBench, and other wind energy V&V experts with the primary goals to: (1) share V&V experience and (2) discuss pathways and prioritization for establishing future IEA Wind tasks in these areas. Topics will be presented and discussed in the following categories:

- Lessons learned from prior validation campaigns for wind farm aerodynamics, rotor aero-elastics, and offshore hydrodynamics;
- Deficiencies in modelling approaches that should be improved through future V&V projects;
- Availability of—and challenges obtaining—experimental datasets, and future measurement needs;
- Ranking of the importance of various phenomena and establishment of validation metrics;
- Techniques and technologies needed to measure data required by the model-validation effort;
- Utilization of high-fidelity models to develop/calibrate/validate engineering models;
- Application of UQ in the model-validation effort; and
- Opportunities for collaborative three-way V&V projects between data, HFM, and engineering models in the areas of wind farm aerodynamics, rotor aero-elastics, and offshore hydrodynamics.

TENTATIVE PROGRAM

The TEM program will include:

- Introduction by hosts (ORE Catapult and NREL);
- Recognition of participants;
- Presentations from participants covering the topics listed above;
- Break-out sessions in the areas of wind farm aerodynamics, rotor aero-elastics, and offshore hydrodynamics for in-depth discussions on the pathways and prioritization for establishing future IEA Wind V&V collaborative(s);
- Summarizing the results of the breakout sessions;
- Discussing next steps; and
- An optional visit to the Samsung 7-MW demonstration offshore wind turbine in Levenmouth operated by ORE Catapult.

INTENDED PARTICIPATION

Participants will include representatives from industry (OEMs, consultants, developers, and certifiers) and research (laboratories, universities, and government), including from:

- The OC5 project of IEA Wind Task 30;
- The WakeBench project of IEA Wind Task 31; and
- Other wind energy V&V experts.

Each participant is expected to give a brief 15-30 minute presentation, including questions and a discussion, of their experience in one or more of the topics listed above. However, the length of time available is somewhat dependent on the number of presentations to be given.

EXPECTED OUTCOMES

One of the goals of the meeting will be to gather existing knowledge on the subject and come up with suggestions and recommendations on how to proceed with future developments. Based on the above, a document will be compiled, containing:

- Presentations by participants;
- A compilation of the most recent information on the topic;
- Main conclusions reached in the break-out sessions; and
- Plans for IEA Wind's future role(s) in this topic.

2. AGENDA

Time	*Topic*	*Presenter*	*Organization*
Wednesday, September 6			
8:30	*Arrival / Check-In*		
9:00	Welcome and Introductions		
9:30	IEA Wind Task 11 - Base Technology Information Exchange	Davy Marcel	PLANAIR SA
9:45	Introduction to TEM #88	Jason Jonkman / Carlos Rodrig	NREL / ORE Catapult
10:00	Findings from IEA Wind Task 30 "OC5" and Plans for OC6 - Focus on Hydrodynamics	Amy Robertson	NREL
10:30	*Break*		
10:45	Findings from IEA Wind Task 29 "Mexnext" and Plans for Use of the DANAERO Database	Helge Madsen	DTU Wind Energy
11:15	IEA Task 31 "Wakebench" V&V Framework for Wind Farm Flow Models: Towards Phase 3	Javier Sanz Rodrigo	CENER
11:45	Comparison of Wave Tank Tests, CFD and Engineering Model Computations of Various Floaters and Mooring Line Dynan	Tor Anders Nygaard	IFE
12:05	V&V Process in the A2e Initiative	David Maniaci	Sandia National Laboratories
12:25	*Lunch*		
13:20	Calibration and Validation of FAST.Farm Against SOWFA	Jason Jonkman	NREL
13:40	Deficiencies in Modelling Approaches That Should be Improved Through Future V&V Projects	Carlos Rodriguez	ORE Catapult
14:00	Real-Time Hybrid Model (ReaTHM®) Testing of a Braceless Semi-Submersible Wind Turbine: Experimental Approach and	Erin Bachynski	NTNU
14:20	Numerical Wind Farm Flow Simulation - Development and Validation of a New Wake Model for Industrial Application	Wolfgang Schlez	ProPlanEn
14:40	Experience from Verification of New BEM Implementation in the Bladed Code--The Need for Further Validation of Dynan	Patrick Rainey	DNV GL
15:00	Aeroelastic code validation – A mixed collection of examples	Torben J.Larsen	DTU Wind Energy
15:20	Introduction to Break-Out Sessions	Jason Jonkman / Carlos Rodrig	NREL / ORE Catapult
15:35	*Break*		
15:50	Break-Out Session #1		
17:20	*Adjourn for the Day*		
19:20	*Dinner at Howies, Waterloo Place*		

Thursday, September 7			
8:30	*Arrival / Check-In*		
9:00	Comprehensive Field Measurements on Research Turbines and Large Prototypes	Christian Kress	Fraunhofer IWES
9:20	New Model Tests for V&V of HFM and Engineering Tools Focusing on the Hydrodynamics Response of a Semisubmersibl	Sebastien Gueydon	MARIN
9:40	High-Fidelity Models Used in Wind Industry	Francisco Navarro Villora	Siemens Gamesa Renewable Energy
10:00	NAUTILUS Semisubmersible Experimental Tests at Ifremer	Josean Galvan	Tecnalia Resesarch & Innovation
10:20	Wind Farm Engineering Modeling and Validation with CFD - Objectives and Methodology	Frederic Blondel & Marie Cathe	IFPEN
10:40	*Break*		
10:55	Key Challenges Related to Qncertainty, Modeling, and Validation in Offshore Wind	Michael Muskulus	NTNU
11:15	Coupled Dynamics of Wind Turbines: a Multi-Perspective Approach	Cristian Guillermo Gebhardt	Leibniz University of Hannover
11:35	Experience with wake model benchmarking in IEA Task 31: Wakebench	Pat Moriarty	NREL
11:55	Power Cable Configuration Design Aspects	Jacob Qvist	4subsea
12:15	Validation for Multi-Fidelity Structural Analysis Process	Martin Rädel	DLR
12:35	*Lunch*		
13:30	Break-Out Session #2		
15:00	*Break*		
15:15	3D CFD Simulations in Comparisson to Large Scale Tests for Various Types of Breaking Waves - Capabilities and Limitatio	Arndt Hildebrandt	Leibniz University of Hannover
15:35	The Role of Wind Tunnel Testing in the Validation and Calibration of Models	Carlo Bottasso	TUM
15:55	Wind Farm Blockage: Measurement, Prediction, and Impact on Energy Production	James Bleeg	DNV GL
16:15	Model Testing and Validation for a TLP Concept	Pauline Bozonnet	IFPEN
16:35	Continuous Validation of an Inhouse Software for Wind Turbine Load Calculation	Philipp Thomas	Fraunhofer IWES
16:55	Implementation Aspects of the Blade Element Momentum BEM Model for Aeroelastic Simulations of Large Wind Turbin	Helge Madsen	DTU Wind Energy
17:05	CL-Windcon Project	Javier Sanz Rodrigo	CENER
17:15	*Adjourn for the Day*		
19:00	*Dinner at Vittoria on the Bridge*		
Friday, September 8			
8:30	*Arrival / Check-In*		
9:00	Aeroelastic Simulation of Wind Turbines - Tool Development and Validation	Oliver Hach	DLR
9:20	Characterization of and checks on sensor data for model validation	Jean-Baptiste Le Dreff	EDF R&D
9:40	Break-Out Session #3		
11:10	*Break*		
11:25	Presentation from Wind-Farm Aerodynamics Group	Pat Moriarty	NREL
11:40	Presentation from Rotor Aeroelastics Group	Helge Madsen	DTU Wind Energy
11:55	Presentation from Offshore Hydrodynamics Group	Amy Robertson	NREL
12:10	Group Discussion		
12:35	*Lunch*		
13:30	*Optional Tour of ORE Catapult's 7-MW Levenmouth Demonstration Turbine*		
17:00	*Adjourn*		

3. LIST OF PARTICIPANTS

The meeting was attended by 32 participants from 9 countries. Following is the list of participants and their affiliations.

Name	*Initials*	*Organization, Country*
Helge Aagaard Madsen	HAM	DTU Wind Energy, Denmark
Torben Juul Larsen	TJL	DTU Wind Energy, Denmark
Frederic BLONDEL	FB	IFPEN, France
PaulineBozonnet	PB	IFPEN, France
Marie CATHELAIN,	MC	IFPEN, France
Jean-Baptiste Le Dreff,	JBLD	EDF R&D, France
Carlo L. Bottasso	CLB	Technical University of Munich, Germany
Francisco Navarro Villora	FNV	Siemens Gamesa Renewable Energy, Germany
Christian Kress	CK	Fraunhofer IWES, Germany
Philipp Thomas	PT	Fraunhofer IWES, Germany
Arndt Hildebrandt	AH	Ludwig-Franzius-Institute of Leibniz Universität Hannover, Germany
Cristian Guillermo Gebhardt	CGG	Leibniz Universität Hannover, Germany
Martin Rädel	MR	DLR, Germany

Oliver Hach	OH	DLR - German Aerospace Center, Germany
Sebastien Gueydon	SG	MARIN (Maritime Research Institute Netherlands), Netherlands
Erin Bachynski	EB	NTNU, Norway
Tor Anders Nygaard	TAN	Institute for Energy Technology, Norway
Jacob Qvist	JQ	4subsea, Norway
Michael Muskulus	MM	NTNU, Norway
Josean Galvan	JG	Tecnalia Research & Innovation, Spain
Javier Sanz Rodrigo	JSR	CENER, Spain
Davy Marcel	DM	IEA wind task 11, Switzerland
Peter Greaves	PG	ORE Catapult, United Kingdom
Patrick Rainey	PR	DNV GL, United Kingdom
Carlos Rodriguez	CR	ORE Catapult, United Kingdom
James Bleeg	JB	DNV GL, United Kingdom
Wolfgang Schlez	WS	ProPlanEn, United Kingdom
David Maniaci	DM	Sandia National Laboratories, United States
Patrick Moriarty	PM	NREL, United States
Amy Robertson	AR	National Renewable Energy Laboratory, USA
Jason Jonkman	JJ	National Renewable Energy Laboratory (NREL), USA
Michael Robinson	MR	DOE/WETO, USA

4. SUMMARY AND Q&A

As background, physics-based models of varied fidelity are needed to advance wind-energy technology. Computationally efficient engineering tools can support an iterative and probabilistic design process and optimization, but simplifying assumptions bring limitations, so verification and validation (V&V) is key to their accuracy. High-fidelity modeling (HFM) also supports technology development and is a useful V&V compliment to experimental data by extracting underlying physical phenomena, but HFM also requires V&V. Limitations in wind energy applications requiring further tool development and V&V include:

- Atmospheric flow and wake/array modelling for power and loads of turbines in wind plants;
- Aero-elastic modelling of modern, large, flexible, and aero-elastically tailored rotors; and
- Hydrodynamic fluid-structure modelling of offshore wind support structures in severe

sea states.

Offshore Renewable Energy (ORE) Catapult and the National Renewable Energy Laboratory (NREL) co-hosted IEA Wind TEM #88 in Edinburgh, UK on September 6-8, which focused on three-way V&V between data, HFM, and engineering models in the areas of wind-farm aerodynamics, rotor aero-elastics, and offshore hydrodynamics. The meeting brought together 32 experts from 9 countries to share V&V experience and to discuss pathways and prioritization for establishing future IEA V&V collaboratives. Further collaborative V&V of models of varying fidelity based on quantitative metrics is needed—along with the associated experimental data—to ensure model suitability, to classify limitations and quantify uncertainty, and to identify future development needs. Presentations and break-out group discussions covered:

- Lessons learned from prior validation campaigns;
- Deficiencies in modelling approaches that should be improved through future V&V projects;
- Availability of—an challenges obtaining—experimental datasets, and future measurement needs;
- Ranking of the importance of various phenomena and establishment of validation metrics;
- Techniques/technologies needed to measure data required by the model-validation effort;
- Utilization of HFM to develop/calibrate/validate engineering models;
- Application of uncertainty quantification (UQ) in the model-validation effort; and
- Opportunities for collaborative three-way V&V projects between data, HFM, and engineering models.

Based on break-out group discussions, the meeting resulted in a clear direction for future collaborative V&V under IEA Wind, including the following (further details will be worked out in each area of the next several months):

- Wind-Plant Aerodynamics: The group agreed to extend Task 31 (WakeBench) once the original Task concludes in 2018. A Task extension proposal will be submitted to the IEA Wind Executive Committee (ExCo) at the spring 2018 ExCo meeting. Characteristics of the extension include (1) development of an international phenomena importance and ranking table (PIRT); (2) inclusion of a range of model fidelities, including industry engineering tools; (3) improved benchmarking process (OC5-like) with clear calibration, blind comparison, and iteration steps; (4) better time-resolved higher resolution quantitative comparisons; (5) inclusion of new validation metrics for power and loads; and (6) use of new datasets;

- Rotor Aero-Elastics: The group agreed to extend Task 29 (MexNext), which recently concluded, and will submit a Task extension proposal to the IEA Wind ExCo at the fall 2017 ExCo meeting. Characteristics of the extension include (1) use the DANAERO data base initially, perhaps with addition phases using data from ORE Catapult or DLR; (2) focus on aerodynamic and aero-elastic response to turbulent, sheared, and yawed inflow; (3) investigation of 2D and 3D airfoil characteristics and the laminar-to-turbulent transition; (4) consideration of aero-elastically tailored blades; and (5) consideration of extreme loading of blades in standstill conditions.

- Offshore Hydrodynamics: The group agreed to extend Task 30 (OC5) once the original Task concludes in 2018. A Task extension proposal (for OC6) will be submitted to the IEA Wind ExCo at the spring 2018 ExCo meeting. Characteristics of the extension include (1) more focused validation objectives, with a clear distinction between hydrodynamics and aerodynamics; (2) quantification of experimental uncertainty; (3) inclusion of high-fidelity models to understand and improve deficiencies in engineering models; and (4) use of new datasets (including from the MaRINET2-funded retesting of the OC5-DeepCwind semisubmersible at MARIN).

The following summarizes the main results and Q&A discussions from each presentation in the agenda.

Davy Marcel – IEA Wind Task 11
- Promote information exchange for emerging wind energy R&D
- In future, all countries in IEA Wind will be part of Task 11

Q&A: -

Carlos Rodriguez and Jason Jonkman – Introduction to TEM #88
- Advantages on uniting Offshore, Aero-elastics, and Wind Farm in one TEM because they try to solve similar V&V problems with similar methods and tools.
- There is room for better modelling and understanding discrepancies between engineering tools e.g. Bladed, FAST and HAWC2.
- There is a need to collaborative use data and HFM to validate engineering tools.

Q&A: -

Amy Robertson – IEA Wind Task 30 OC5
- For Aero: FAST, Bladed, HAWC2. For Hydro: OrcaFlex, Sesam, …
- Description of OC3, OC4, OC5; proposal for a new C for OC6.
- We need to assess simulations, understand deficiencies on codes.
- Verification with OC3 and OC4: comparing tools one another. Different offshore platforms.
- Validation: OC5: experiment with tow tank and real WTs. Unfortunately, only 3rd

party measurements are available. Need to set a good metric (tolerances) to validate.

Q&A:
SG – Need both uncertainty in data, and uncertainty in simulation
MM – Uncertainty due to physical limitations, as well as numerical inaccuracies
AR – All models need to get to a converged solution
PM – Are all models similar fidelity?
AR – Differing fidelities for hydro and structure, but no CFD yet in OC5.
SG – Importance of the calibration of the waves – will have large impact on calculated loads; uncertainty/sensitivity/inaccuracy in measured data.
*CR – What scales are involved e.g. k*R?*
*AR – k and R refer to wavenumber and cylinder radius; k*R refers to wave steepness*
PM – Verification – Were the verification studies of OC4 used to identify the needed validation in OC5?
AR – OC4 semi and OC5 validation where for the same system, but otherwise we used the data we had
CGG – Are the models coupled?
AR – All models where fully coupled, but different tests focused on different coupled interactions.
CGG – Two way strong coupling?
AR – In most cases, yes
SG – Perhaps the sixth "C" in OC6 could stand for "coupling"?

Helge Madsen – IEA Wind Task 29 MexNext

- History: task 14-18-20 NASA-AMES wind tunnel - aerodynamic model enhanced.
- Testing in Mexico and New Mexico in controlled conditions. Additionally testing in low speed wind tunnel in Germany.
- Sought correlation between experiments and axial momentum theory.
- Take into account participants code-model characteristics. Loads validation BEM, FVW, AM, CFD_turb, CFD_trans.
- Synergies detected between different Tasks.
- Data delivered to different countries.
- Aerodynamics for 10MW+ are challenging.
- Old data sets are not characteristic for large WTs (structurally, aerodynamically,).
- Tests with surface pressure and inflow probes in one blade (LM 38.8).
- Comparison measurements with Ellypsis CFD code.
- Uncertainty introduced from different St. Dev. Coming from measurements and Simulations.

Q&A:
JJ – What is meant by "uncertainty" here?
HAM – Std deviation of data; std deviation b/n codes.
PG – What structural measurements were included?
HAM – Strain gages and accelerometers.
JSR – Is the DANAERO turbine still installed?
HAM – The test blade has been removed; can't do more tests; would like to do standstill tests under extreme parked/idling conditions, but haven't done it yet.
SG – Low Re# in wind tunnel versus full-scale Re; lessons learned?

HAM – There is uncertainty in transition between laminar and turbulence; RANS needs to be improved in transition, especially under turbulent inflow.

Javier Sanz Rodrigo – IEA Wind Task 31 WakeBench

- WP0, WP1 (meso-micro), WP2 (NREL), WP3 (VV & VQ).
- Establish a model evaluation protocol.
- Maybe try to go from operational problems to theory explanations, instead of the usual.
- Ambidextrous V&V (NEWA).
- GABLS3. Boundary layer characteristics. Rotor equivalent wind speed.
- Published results and <u>tools for validation</u>.
- Towards Phase 3 so far.
- Maybe LES needed?
- Data from Alpha Ventus, A2e-SWIFT.

Q&A:
TJL – Benchmarks are tied to model being applied; focus on RANS or linear flow models e.g. steady-state power, but not on 10-minute time series; missing focus on LES or DWM; more focus on energy production, not loads.

JSR – Yes, the focus was on energy production up front, will move into other areas in the future.

PM – This reflects importance of PIRT; including unsteady models as important will raise importance in this task.

JSR – The current R&D focus on wind-plant control is also making this important.

Tor Anders Nygaard – Comparison of Wave Tank, CFD, and Engineering Models for Floaters

- Using 3D floats, FEM, Euler-Bernuilli beam theory.
- Code to code verification: OC3, OC4, OC5.
- Data available for validation with NOWITECH.
- Pulleys may introduce uncertainties during tests.
- Used dlc 'surge heave' as characteristic.
- Hydrodynamics for regular wave loading match nicely. CFD is doing well.

Q&A:
SG – Do the pulleys induce friction in moorings?

TAN – Yes, problems required change in moorings; pulley's brought about hysteresis in moorings; hysteretic damping is included at the anchor point.

TAN – CFD focus is on how to generate the correct wave kinematics at the structure.
AR – What are the engineering models missing compared to CFD?

SG – Engineering models miss suction behind the cylinder.

TAN – CFD quite good at capturing damping in free-decay.

SG – Yes, but the CFD result is still not perfect

TAN – Yes, but this may be to inaccuracies in the mooring modeling, not CFD.

SG – Has had frustration with CFD, e.g. checking that the calculation is correct.

TAN – CFD has been misused a lot; but experts can get correct results.

AR – We need a recommend practice on how to do CFD correctly.

AR – Damping for engineering models; should it be set based on free-day; how about frequency dependence?

TAN – Yes, frequency-dependent damping would also be useful to calculate.

David Maniaci – A2e V&V Process

- V&V Overview: real environment range always wider than tested/validated.
- Established a prioritization process.
- PIRT leads to validation hierarchy.
- PPEM: Prioritized Phenomenon Experiment Mapping
- Full scale > scale down to simple model, find statistic correlations > back to full scale (surrogate).

Q&A: -

Jason Jonkman – FAST.Farm Development and V&V

- 20 coefficients used to fine-tuning this model.
- Capable of real time simulations.
- 9 SOWFA calibration cases took 1 year.
- Differentiate unstable \ stable \ neutral.
- Defects on axial wake model/predictions.

Q&A:

TAN – How is wake superposition done and is equilibrium reach in the far wake?

JJ – Yes, FAST.Farm uses a root-sum-squared approach, so, it the wake loss tapers off to equilibrium downstream.

HAM – LES is used in place of TurbSim?

JJ – Yes, to capture the varying ambient flow across the entire wind farm.

Carlos Rodriguez – Deficiencies in Modelling Approaches That Should be Improved Through Future V&V Projects - Carlos Rodriguez - ORE Catapult

- Had to rely on DNV data (not as many loads cases as wished, we had to rely on wind speed measurement etc.)
- Operator is SgurrEnergy

Q&A:

MM – Are the differences between measurements and simulations because of the software? Could it not be the model inputs e.g. uncertainties?

CR – Yes certainly; the SCADA data has not been well calibrated.

MM – Is there a strategy to improve the models?

CR – Controller is a big source of uncertainty.

MM – Can the controller be updated to better match the results?

CR – Currently the controller is a black box; engaging in DNV-GL to perhaps open-up the controller so that ORE Catapult can play with the controller; also, an open-source controller could be tuned to mimic the behavior of the real controller.

AR – Do you have access to the controller?

CR – We have access to what the SCADA data is measuring; have access to the controller DLL; may not be the same logic in the real turbine

AR – Suggests doing more tuning of the controller up front.

SG – Is the same controller used in FAST and Bladed?

CR – No, the controller so far has been different, but will be the same going forward.

Erin Bachynski – Real-Time Hybrid Model Testing

- 0.004 s. delay from procedure adds some damping > pitch discrepancies.
- In the experimental model, we measure tensions also at the mooring
- When the actuators are turned on but no load is applied, surge gave our best results
- In case of constant wind, there was a change we expected
- Coefficients give both drag and damping

Q&A:

SG – Can you explain why surge is so much better than pitch for this system?

EB – Pitch frequency is higher, so, a delay in aerodynamic actuation influences the level of damping. This is being addressed by better predictive control; better measurements of the delay can also be compensated.

PR – Are you closing the loop e.g. measuring accelerations? Is the rotor inertia physical or numerical?

EB – Yes, inertia is physical; numerical inertia would require better actuation.

SG – Are gyroscopic effects included?

EB – Not found to be important, but could be captured by a spinning disk.

TJL – Does the inertia of the actuator lines cause problems?

EB – The actuator lines are pretensioned.

Wolfgang Schlez – Numerical Wind Fam Flow Simulations for Industrial Applications

- Wake blaster: time domain. 10 min. averages.
- Intention to fill gap between widely used Jensen\Park model and LES.
- Feeding model with historical SCADA data, filtered and analysed.
- Useful for 30 min. forecasting.

Q&A:

SG – How are the wind turbines modeled?

WS – Wind turbines induce a momentum deficit, based on a Ct curve.

TJL – How is turbulence variation accounted for?

WS – TI is an input parameter; turbulence is captured through an eddy viscosity model. The solution is steady-state, but solved via time stepping.

Patrick Rainey – Experience from Verification of a new BEM implementation in Bladed; Need for Further Validation of Dynamic Stall

- Bladed 4.8 includes structural deflection in the calculation of section orientation.
- Dynamic stall model based on Theodorsen theory.
- Beddoes – Leishmann, Kirchoff flow.
- Lack of data to validate these models. CLOWT could answer these questions.

Q&A:
TJL – Agrees with the deep stall problem, and limitations of the Beddoes-Leishman model; problem in load case 6.2; CFD simulations have shown that edgewise vibrations because of VIV and high wind-speed, but the CFD calculated amplitudes of oscillation are much smaller than engineering models; very few real word data, which is need data at this condition

PR – Haven't seen many practical industry examples of problems in this area, so, little funding has been available for testing; even though models predict it, industry just doesn't believe it will happen and believes the models are wrong in this area.

PR – Any work to turn CFD into an engineering model?

HAM – DTU has done some work; can provide references.

CR – ORE Catapult may be able to measure this.

Torben Larsen – Aeroelastic Code Validation – A Mixed Collection of Examples

- Able to linearize lidar measurements to build a 3D measured turbulent windfield.

Q&A: -

Christian Kress – Comprehensive Field Measurements on Research Turbines – Smart Blades

- Fraunhofer IWES intro.
- Smartblades2 intro: 1) bend twist-coupling, 2) active TE flaps and 3) passive and active flaps included.
- Manufacturing 4 blades heavily instrumented. 1 to be tested including calibration of instrumentation.
- Planned measurements of performance, loads, deflections (optical SSP sensors), lidar, met mast, incident flow probes, usual load cases.
- Future projects with Adwen 180m 8MW WT. Internal FEM model, CFD and engineering models to be validated.

Q&A:
JJ – What are the range of model fidelities being validated?

CS – FEM models

PT – FEM, CFD, and engineering models.

Sebastien Gueydon – New Model Tests of the DeepCWind Semisubmersible at MARIN

- Large underestimates of surge and drift loads.
- Drag loads measured on a floater with different shaped elements.
- 1 week of testing. Focus on drag loads. Based on OC4.
- Numerical uncertainty for surge motion, human intervention is a source of uncertainties too.

Q&A:
EB – The initial condition in CFD is at the offset position; may not match experiment?

SG – Yes, the technician has some influence; helps to look at coupling between surge, pitch, and heave.

TJL – Benchmark comparisons, treat structure as rigid, don't look at internal loads needed for design; can this be included in model tests?

SG – Don't consider because semi is rigid; MARIN can consider structural flexibility *for structures that are flexible e.g. container ship; calibrate frequencies to design; don't reproduce design e.g. steel thickness, but mimic global response.*

TJL – Is the full-scale semi really stiff?

SG – It may be easier to capture the full-scale stiffness at larger model scales.

Francisco Navarro Villora – HFM Used in the Wind Industry

- Idea generation > industry, universities, experts > innovation portfolio.
- Start design implementation with very simple models > engineering models > HFM models.
- Certify design and build up a prototype. Very difficult to differentiate measure from simulation inaccuracies during validation. Virtual prototyping (checking ACs with HFM) may be a solution.
- CFD used to tune up LFM.

Q&A:

JB – Is the RANS/LES software for aerodynamics and aeroacoustics based on commercial or open-source software?

FNV – Unsure.

Josean Galvan – NAUTILUS Semisubmersible Tests

- Company intro.
- Concept advantage: is smaller than other semisubs.
- Active ballast to guarantee a stable platform for WT.
- WTs air side not yet implemented.
- A bigger scale experiment planned.
- Used Hydrodyn, Ocraflex, OpenFoam, DualSPHysics with MoorDyn

Q&A:

AR – Trim system; active ballasting?

JG – Include sensors to active control water ballasting to keep platform horizontal.

JJ – How do you use engineering models and CFD to complement each other?

JG – If CFD is shown to work well, use CFD in lieu of tank testing to calculate hydrodynamic coefficients

JBLD – Have you checked the ballast system for resonance with waves?

JG – Active ballast is too slow (15 minutes), so no direct interaction with wave frequencies; the active ballast system is not modeled directly.

SG – Does the draft change with active ballast?

JG – Heave changes very little (less than a meter).

CR – Will you include a wind turbine in your tank testing?

JG – Small motion permits most any turbine.

Frederic Blondel – Improving BEM Yaw Model with NewMexico and CFD
& Marie Cathelain – Wind Farm Engineering Modeling and Validation with CFD

- Alternatives to BEM: Vortex methods (CASTOR, lifting line method) have drawbacks > CFD.

- Propose to include contribution of hub vortex in yaw model simulations.

Q&A: -

Michael Muskulus – Key Challenges Related to Uncertainty, Modeling, and Validation in Offshore Wind

- Describes all measurements uncertainties (wind hub – met mast, max,..) and comes to a 10% between model and measurements.
- Big uncertainty coming from: measurements are capturing low freq. signals, while rigid matrix that we want to describe is driven by high freq. effects.

Q&A:
AR – The bias in measurements can be eliminated through calibration; some biases are hard to identify because repeating tests can't resolve it; How to resolve bias?

> *MM – Some terms e.g. bending moment easy to address through yaw tests; often need different kinds of tests aiming to measure the same thing.*

Christian Guillermo Gebhart – Coupled Dynamics Models – A Multi-Perspective Approach

- FEM, multilayer, multibody, time-domain, boundary method.
- Beams + Surfaces: topology incompatibilities.
- Validated against Abaqus and Ansys.
- In publication process.
- Conclusions: advances and multidisciplinary approaches are still necessary

Q&A:
JG – Are the tower designs conical or straight?

> *CGG – Building 3 towers, including a conical; need strong actuators – looking at real-time load application.*

PB – How does tight coupling compare to loose coupling between aero and structural models?

> *CGG – In loose coupling, you can predict flutter onset, but beyond onset, loose coupling doesn't work; need tight coupling for post critical behavior.*
> *CGG – Can use the same Boundary Element Method code for hydrodynamics; added-mass effect complicates coupling e.g. tight coupling needed.*

Pat Moriarty – Experience with Wake Model Benchmarking in IEA Task 31: WakeBench

- 14+ models studied for benchmarking.
- Wind Parks used depend on interest of funders. Classical Wind Park "Horns Rev" among them.
- Comparing models for Δ=5°and Δ=30° gives a contra-intuitive result: models are more similar for the latter. Explanation: presumably they are tuned for that.
- Different models show similar behaviour. Results translated to mean error to quantify differences.
- LES not always better, only if fine-tuned.

- Uncertainty quantification is necessary

Q&A:

TJL – In the Horns Rev data, why is there bigger uncertainty in the narrow wind band than wider band; the wider the band, the more you capture the free stream effect. For a given downstream distance, does the plot show the average of all turbines, or only one row of the wind farm?

PM – Processing of the data is a key part of the model validation challenge.

PM – Measurements show average of all rows except the end rows; the modeling results are influenced by how the modelers chose to make use of the data.

Jacob Qvist – Power Cable Configuration Design Aspects

- Dynamics just not included in cable testing

Q&A:

FVN – Cable failures?

JQ – Includes infield cables to turbines.

FVN – Has some concern about cables inside monopiles.

JG – Can spectral analysis be useful for cable design?

JQ – Hysteretic nonlinearities important; time-domain simulation important

CGG – Is Hysteresis influenced by cable extension or multiple layers within cable?

JQ – Both.

Martin Radel – Validation of Multi-Fidelity Structural Analysis Process

- DLR existing tools to combine aero and structural analysis now used for wind.
- Combine shell and more detailed models.

Q&A: -

Arndt Hildebrandt – 3D CFD of Breaking Waves

- Combine FEM (which simulates wave until braking) with CFD (which takes it from there, where FEM brakes down).
- Boundary layers across wave must be taken into account and be parametrized.
- CFD are CPU expensive but richer than measurements.

Q&A:

SG – Does the CFD model account for air compressibility?

AH – A volume of fluid method has been applied, but the fluids are not compressible; with air bubbles, the numerical solution starts to flutter.

Carlo Bottasso – The Role of Wind Tunnel Testing in the Validation and Calibration of Models

- You must accept that your model will have limitations.
- Wind tunnel at Milano University includes active pitch (control) WT and WP models (G0.6, G1, G2).

- All 3 models with control, collective and IPC. Capable of testing terrain roughness

Q&A:

CGG – What kind of control strategy? PID?

CLB – Depends on the experiment; turbines can be PID or LQR; controller is plug and play; likewise for wind-farm controller, including model-free and model-based controls.

James Bleeg – Wind Farm Blockage: Measurement, Prediction, and Impact on Energy Production

- 1st row is considered "clean" (independent form lateral and downwind influence).
- This is not true: we call this effect "Wind Park blockage".
- We estimate an under performance of 2% because of WP blockage.
- Because WP performance is referred to 1st row performance, we estimate a general underperformance of 2% in every WP

Q&A:

FNV – Have you checked sensitivity of blockage to spacing?

JB – Yes, definitely some significant sensitivity.

TAN – Two-way coupling would be more expensive.

JB – Agrees.

DM – Have you considered modeling this with induction? E.g. vortex models would be able to predict deficit upwind of the rotor

JB – Yes, but there is some difference between individual turbine induction and wind-farm scale blockage; doesn't think this would work.

CLB – There are simplified models that are a step change in roughness; could this be applied?

JB – It may work and this is worth looking at, but JB is skeptical that it will work.

Pauline Bozonnet – Model Testing and Validation for a TLP Concept

- Floating platform based on Instant Centre of Rotation to guarantee stability.
- Now validating model with test campaign.
- Deficiencies in down-escalating air side (between maintaining Re or St, chose the latter).
- Modelled with Orcaflex (hydro-elastic) and aero-servo-elastic DeepLinesWind.
- Tests (CFD and tank) show that nacelle stays stable with low waves.

Q&A:

TAN – Is the loss of line tension and snap loads something you're looking at?

PB – Yes, were looking at that.

JJ – Negative damping is a common problem for FOWT, but this system moves the opposite; what is the implication?

PB – Something to look at.

JG – The platform has many elements; is the low-frequency response drag-dominated, or is this 2nd-order hydrodynamics?

PB – Likely some combination of both, but CFD would help here.

Philipp Thomas – Continuous Validation of Inhouse Software for Wind Turbine Load Calculation

- Fraunhofer intro.
- Coupled with DynaLab for HIL tests

Q&A: -

Helge Madsen – Implementation Aspects of BEM for Aeroelastic Simulations of Large Wind Turbines?

Q&A:
JJ – NREL splits the annulus ring into three (one per blade); how is thrust considered when split into more than three?
> *HAM – This approaches applies to generalized dynamic wake.*
> *TJL – For collective pitch, one can just pick the nearest blade; for independent pitch, you can apply a sinusoidal variation.*

EB – Why 1P excitation in turbulence?
> *HAM – Rotational sampling*

Javier Sanz Rodrigo – CL-Windcon Project

Q&A:
PM – What kind of sensing will you use in the closed-loop controller?
> *JSR – Scanning LIDARs, plus usual turbine measurements in the test.*

Oliver Hach – Aeroelastic Simulation of Wind Turbines

Q&A:
HAM – What is the timeframe for the new experimental turbine?
> *OH – Plans have been delayed a bit, but the design is finished and waiting for funding to construct*

TJL – What are the sight conditions?
> *Flat, 40-m rotor on 50-m tower; no nearby obstructions.*

Jean-Baptiste Le Dreff – Characterization and Checks on Sensor Data for Model Validation

Q&A:
JJ – What turbine and substructure is considered here?
> *JBLD – Monopile, grouted transition piece, 2.x-MW turbine; UK wind farm.*

AR – What is the long-term goal?
> *JBLD – Currently focused on validation of models; Re-evaluation of wind turbine data could follow.*

TJL – Trouble with strain gages; a yaw rotation test could be used to convert strain to bending moment; how do you calibrate?

JBLD – Working with the strain gage installers; still need to look into it.
EB – When were the gages installed?
JBLD – Unsure.

Break-Out Group Presentations

Pat Moriarty – Wind-Farm Aerodynamics

Q&A:
TAN – Why is wind-plant blockage shown in green in the PIRT?
PM – This is focused on the deep-array problem.
PM – Loads are not specifically mentioned in the PIRT.

Helge Madsen – Rotor Aeroelastics

Q&A:
JJ – What is the proposal to IEA?
HAM – To use the Task 29 extension as proposed, start with the DANAERO experiment, perhaps adding other turbine datasets e.g. Levenmouth in the future.

Amy Robertson – Offshore Hydrodynamics

Q&A:
CGG – What is important regarding soil-structure interaction?
AR – Flexibility at mudline, expanding beyond p-y curves; need for higher-fidelity models.
TAN – The Norwegian Geotechnical Institute is working on superelements derived from HFM to account for flow hysteresis etc.; communicate through a single node
JG – Wind farm aerodynamics – likely to have local wave elevation in floating offshore wind farm; how would local waves be included in the wind-farm models?
HAM – Engineering models have both wind and waves, but no direct air-sea interface
HAM – The aerodynamics of a tilting of rotor perhaps should be tacked by IEA Wind Task 29.
TAN – OC6 will be more focused on pure hydrodynamics; are tests done without rotor? How to capture aerodynamic damping?
AR – MARINET2 tests are with fixed or prescribed motion.
AR – There is still need for the aero-hydro coupling, but would like to initially start with a hydrodynamics focus; there will likely be both hydro only and aero-hydro cases in the OC6
TAN – Recommends to at least consider the effect of mean thrust and aerodynamic damping in the hydro tests
AR/JJ – Some tests are performed at the displaced position of the structure.

Feedback?
SG – Too much content for a three-day days; could be extended to longer time.

FVN – Will notes will be summarized and presentations compiled into a proceedings?
JJ – Yes.

5. PRESENTATION

IEA Wind Task 11

Base Technology Information Exchange

Presentation for TEM on «Three-Way Verification and Validation Between Data, High-Fidelity Models, and Engineering Models» Scotland

Task 11 OA, Planair SA, Switzerland,
06.09.2017

iea wind

Activities within Task 11

- Main objective : promote and disseminate knowledge on emerging wind energy topics
- Main activities :
  - Help identify new topics of interests
  - Organization of 4 topical experts meetings (TEM) a year on new topics of high interests
  - Coordination the approval process of Recommended Practices

Participating countries
Austria (2018)
Belgium (2018)
Canada (2018)
CWEA (China)
Denmark
Finland
France (2018)
Germany
Ireland
Italy
Japan
Mexico
Netherlands
Norway
Portugal (2018)
South Africa (2017)
South Korea (2018)
Spain
Sweden
Switzerland
United Kingdom
United States

2

Activities within Task 11

- Recent and future TEMs:
  - *#86: Downwind Turbines: 11.2016 hosted by Hitachi (Japan)*
  - *#87: Smart Blades : 04.2017 hosted by DTU (Denmark)*
  - *#88: Three way V&V: 09.2017 hosted by NREL & ORE Catapult (Great Britain)*
  - *#89: Grand Vision for Wind Energy: Next Technology and Infrastructure Challenges to Realize Wind's Full Potential: 10.2017 hosted by NREL (USA)*
- Recommended Practices:
  - RP 17: Wind Farm Data Collection and Reliability Assessment for O&M Optimization (Task 33)
  - RP 18: Floating Lidar Systems (Task 32 in coordination with the Offshore Wind Accelerator initiative)

3

New developments

- Planair SA from Switzerland, operating agent since the beginning of 2017
- Clarification of the organization processes for future TEMs
- Online community platform integrated in the brand new IEA Wind's website (launch foreseen in Autumn 2017):
  - Each expert attending an IEA wind meeting will gain access to the platform → creation of a profile, ability to connect with other experts involved within IEA Wind and to share content
  - Each TEM will have its own dedicated community to facilitate ante- & post-communication around the meeting, exchanges among participants and foster future collaborations
  - The event manager tool on the platform will facilitate future TEMs organization → dedicated website (TEM#89 example)
  - **A dedicated community will be created for TEM#88, you'll be informed per email as soon as the website has been launched**

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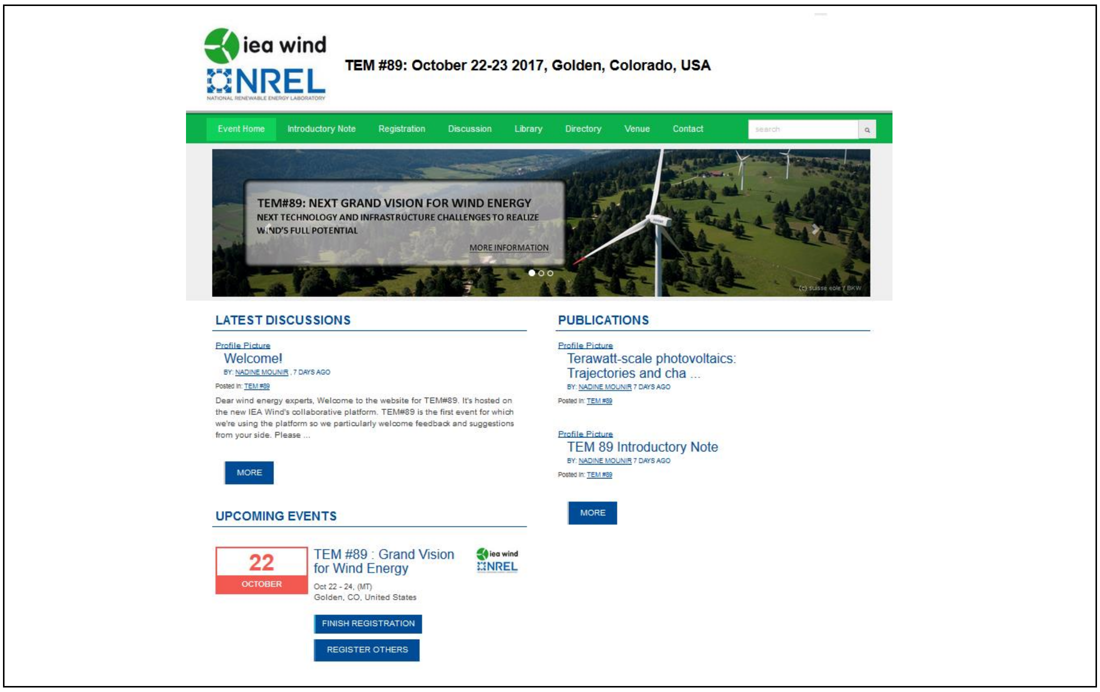
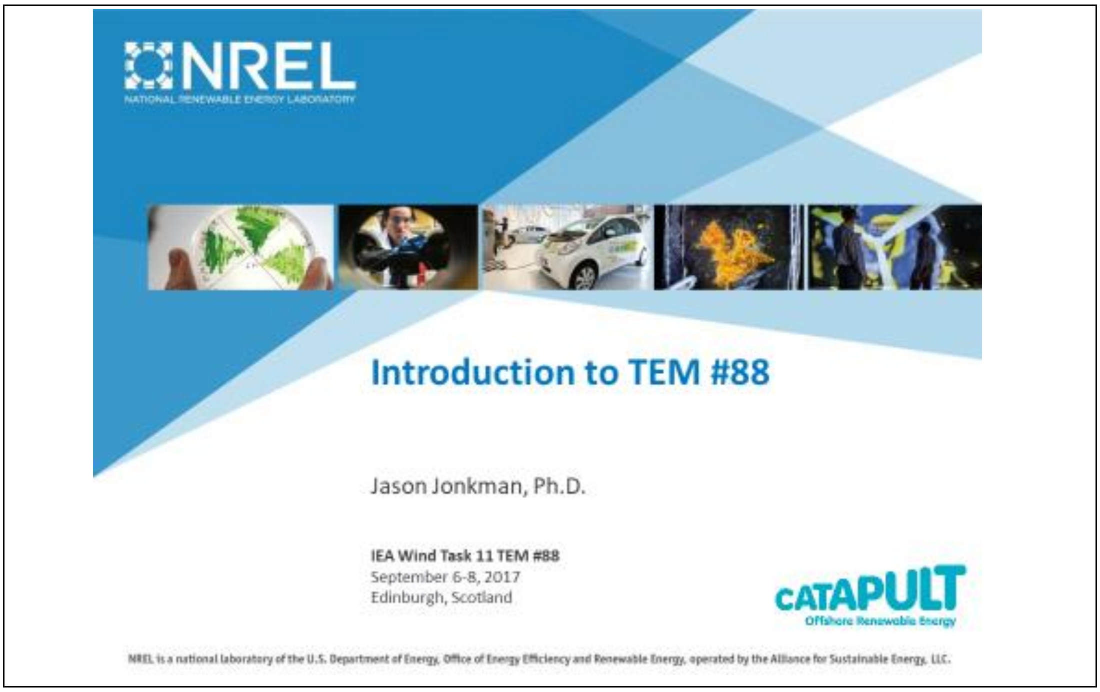
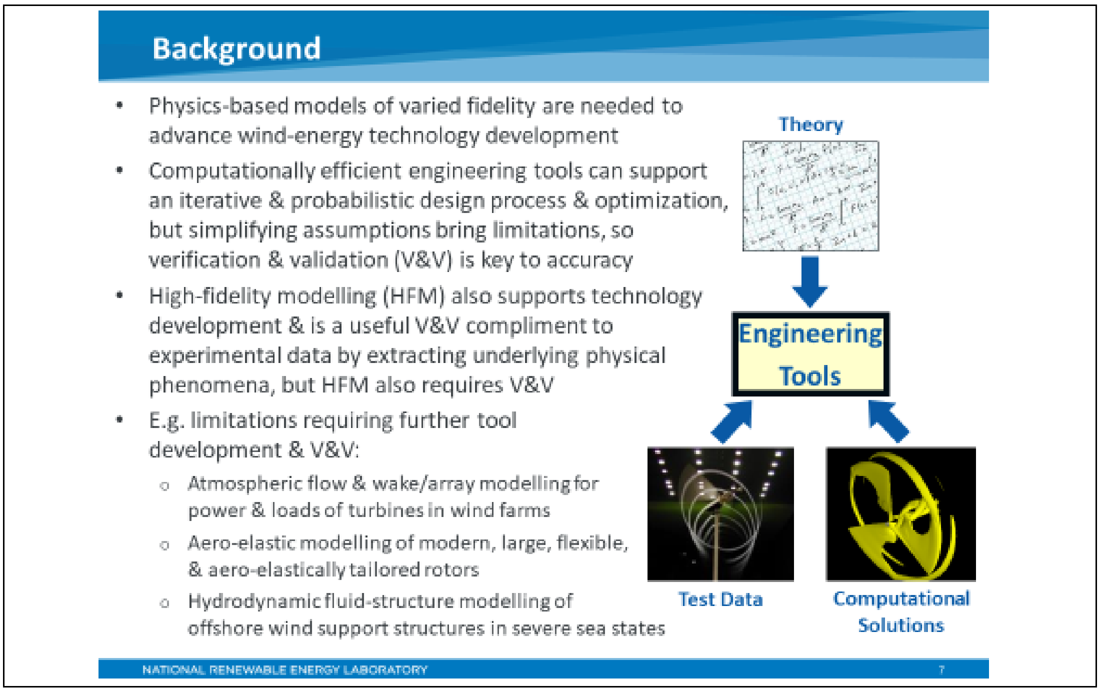

iea wind
NREL
TEM #89: October 22-23 2017, Golden, Colorado, USA
Event Home
Introductory Note
Registration
Discussion
Library
Directory
Venue
Contact
TEM#89: NEXT GRAND VISION FOR WIND ENERGY
NEXT TECHNOLOGY AND INFRASTRUCTURE CHALLENGES TO REALIZE WIND'S FULL POTENTIAL
MORE INFORMATION
LATEST DISCUSSIONS
Welcome!
Dear wind energy experts, Welcome to the website for TEM#89. It's hosted on the new IEA Wind's collaborative platform. TEM#89 is the first event for which we're using the platform so we particularly welcome feedback and suggestions from your side. Please ...
MORE
UPCOMING EVENTS
22
OCTOBER
TEM #89 : Grand Vision for Wind Energy
Oct 22 - 24, (MT)
Golden, CO, United States
FINISH REGISTRATION
REGISTER OTHERS
PUBLICATIONS
Terawatt-scale photovoltaics: Trajectories and cha ...
TEM 89 Introductory Note
MORE


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Introduction to TEM #88
Jason Jonkman, Ph.D.
IEA Wind Task 11 TEM #88
September 6-8, 2017
Edinburgh, Scotland
CATAPULT
Offshore Renewable Energy
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.


Background
Physics-based models of varied fidelity are needed to advance wind-energy technology development
Computationally efficient engineering tools can support an iterative & probabilistic design process & optimization, but simplifying assumptions bring limitations, so verification & validation (V&V) is key to accuracy
High-fidelity modelling (HFM) also supports technology development & is a useful V&V compliment to experimental data by extracting underlying physical phenomena, but HFM also requires V&V
E.g. limitations requiring further tool development & V&V:
Atmospheric flow & wake/array modelling for power & loads of turbines in wind farms
Aero-elastic modelling of modern, large, flexible, & aero-elastically tailored rotors
Hydrodynamic fluid-structure modelling of offshore wind support structures in severe sea states
Theory
Engineering Tools
Test Data
Computational Solutions
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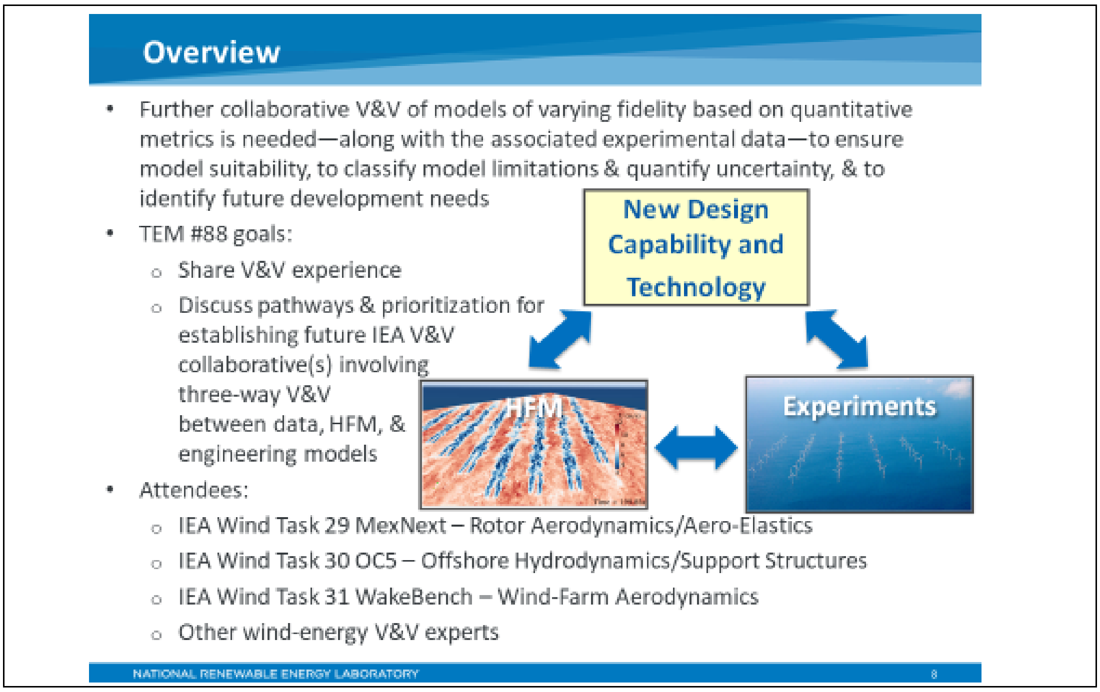
Overview
Further collaborative V&V of models of varying fidelity based on quantitative metrics is needed—along with the associated experimental data—to ensure model suitability, to classify model limitations & quantify uncertainty, & to identify future development needs
TEM #88 goals:
Share V&V experience
Discuss pathways & prioritization for establishing future IEA V&V collaborative(s) involving three-way V&V between data, HFM, & engineering models
Attendees:
IEA Wind Task 29 MexNext – Rotor Aerodynamics/Aero-Elastics
IEA Wind Task 30 OC5 – Offshore Hydrodynamics/Support Structures
IEA Wind Task 31 WakeBench – Wind-Farm Aerodynamics
Other wind-energy V&V experts
New Design Capability and Technology
HFM
Experiments
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Topics for Presentation/Discussion

- Lessons learned from prior validation campaigns
- Deficiencies in modelling approaches that should be improved through future V&V projects
- Availability of—& challenges obtaining—experimental datasets, & future measurement needs
- Ranking of the importance of various phenomena & establishment of validation metrics
- Techniques/technologies needed to measure data required by the model-validation effort
- Utilization of HFM to develop/calibrate/validate engineering models
- Application of UQ in the model-validation effort
- Opportunities for collaborative three-way V&V projects between data, HFM, & engineering models

NATIONAL RENEWABLE ENERGY LABORATORY 9

Agenda – Wednesday, September 6

8:30	*Arrival / Check-in*		
9:00	Welcome and Introductions		
[illegible]	IEA Wind Task 11 - Base Technology Information Exchange	Davy Manzel	PLANAIR SA
[illegible]	Introduction to TEMREE	Jason Jonkman / Carlos Rodriguez	NREL / ORE Catapult
10:00	Findings from IEA Wind Task 30 "OC5" and Plans for OC6 - Focus on Hydrodynamics	Amy Robertson	NREL
10:30	*Break*		
10:45	Findings from IEA Wind Task 29 "Mexnext" and Plans for Use of the DANAERO Database	Helge Madsen	DTU Wind Energy
11:15	IEA Task 31 "Wakebench" V&V Framework for Wind Farm Flow Models: Towards Phase 3	Javier Sanz Rodrigo	CENER
11:35	Comparison of Wave Tank Tests, CFD and Engineering Model Computations of Various Floaters and Mooring Line Dynamics	Tor Anders Nygaard	IFE
12:05	V&V Process in the A2e Initiative	David Maniaci	Sandia National Laboratories
12:20	*Lunch*		
13:20	Calibration and Validation of FAST.Farm Against SOWFA	Jason Jonkman	NREL
13:40	Deficiencies in Modelling Approaches That Should Be Improved Through Future V&V Projects	Carlos Rodriguez	ORE Catapult
14:00	Real-Time Hybrid Model (ReaTHM) Testing of a Braceless Semi-Submersible Wind Turbine: Experimental Approach and Validation Efforts	Erin Bachynski	NTNU
14:20	Numerical Wind Farm Flow Simulation - Development and Validation of a New Wake Model for Industrial Application	Wolfgang Schlez	ProPlanEn
14:40	Experience from Verification of New BEM Implementation in the Bladed Code—The Need for Further Validation of Dynamic Stall Theory	Patrick Rainey	DNV GL
15:00	Introduction to Break-Out Sessions	Jason Jonkman / Carlos Rodriguez	NREL / ORE Catapult
15:15	*Break*		
15:30	Break-Out Session #1		
17:00	*Adjourn for the Day*		
18:00	*Dinner at Howies, Waterloo Place*		

NATIONAL RENEWABLE ENERGY LABORATORY 10

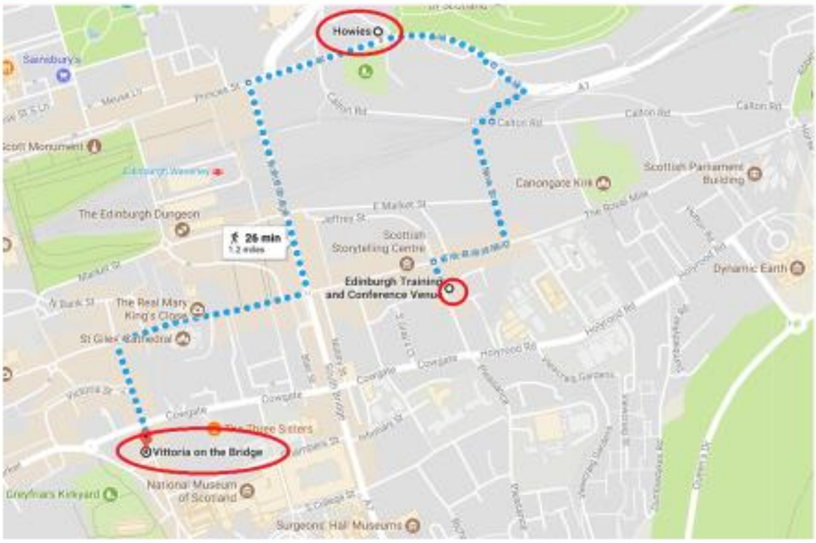
Agenda – Thursday, September 7

8:30	*Arrival / Check-in*		
9:00	Comprehensive Field Measurements on Research Turbines and Large Prototypes	Christian [illegible]	Fraunhofer IWES
9:20	New Model Tests for V&V of HF Mand Engineering Tools Focusing on the Hydrodynamic Response of a Semisubmersible Floating Foundation for Wind Turbines	Sebastien Gueydon	MARIN
9:40	High-Fidelity Models Used in Wind Industry	Francisco Navarro Villasa	Siemens Gamesa Renewable Energy
10:00	NAUTILUS Semisubmersible Experimental Tests at Bremen	Joseba Galván	Tecnalia Research & Innovation
10:20	Wind Farm Engineering Modeling and Validation with CFD - Objectives and Methodology	Frederic Blondel & Marie Cathelain	IFPEN
10:40	*Break*		
10:55	Key Challenges Related to Uncertainty, Modeling, and Validation in Offshore Wind	Michael Muskulus	NTNU
11:15	Coupled Dynamics of Wind Turbines: a Multi-Perspective Approach	Cristian Guillermo Gebhardt	Leibniz University of Hannover
11:35	Experience with scale model benchmarking in IEA Task 31 Wakebench	Pat Moriarty	NREL
11:55	Power Cable Configuration Design Aspects	Jacob Qvist	4subsea
12:15	Validation for Multi-Fidelity Structural Analysis Process	Martin Rädel	DLR
12:35	*Lunch*		
13:30	Break-Out Session #2		
15:00	*Break*		
15:15	3D-CFD Simulations in Comparison to Large Scale Tests for Various Types of Breaking Waves - Capabilities and Limitations	Arndt Hildebrandt	Leibniz University of Hannover
15:35	The Role of Wind Tunnel Testing in the Validation and Calibration of Models	Carlo Bottasso	TUM
15:55	Wind Farm Blockage: Measurement, Prediction, and Impact on Energy Production	James Bleeg	DNV GL
16:15	Model Testing and Validation for a TLP Concept	Pauline Bozonnet	IFPEN
16:35	Continuous Validation of an Inhouse Software for Wind Turbine Load Calculation	Philipp Thomas	Fraunhofer IWES
16:55	Implementation Aspects of the Blade Element Momentum BEM Model for Aeroelastic Simulations of Large Wind Turbines	Helge Madsen	DTU Wind Energy
17:05	CL-Windcon Project	Javier Sanz Rodrigo	CENER
17:25	*Adjourn for the Day*		
19:00	*Dinner at [illegible] the Bridge*		

Agenda – Friday, September 8

8:30	*Arrival / Check-in*		
9:00	Aeroelastic Simulation of Wind Turbines - Tool Development and Validation	Oliver Hach	DLR
9:20	Characterization of and checks on sensor data for model validation	Jean-Baptiste Le Dreff	EDF R&D
9:40	Break-Out Session #3		
11:10	*Break*		
11:25	Presentation from Wind-Farm Aerodynamics Group	Pat Moriarty	NREL
11:40	Presentation from Rotor Aeroelastics Group	Helge Madsen	DTU Wind Energy
11:55	Presentation from Offshore Hydrodynamics Group	Amy Robertson	NREL
12:10	Group Discussion		
12:40	*Lunch*		
13:30	*Optional Tour of ORE Catapult's 7-MW Levenmouth Demonstration Turbine*		
17:00	*Adjourn*		

Maps



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CATAPULT Offshore Renewable Energy

Carpe Ventum!

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www.nrel.gov

NREL NATIONAL RENEWABLE ENERGY LABORATORY

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1977 - 2017

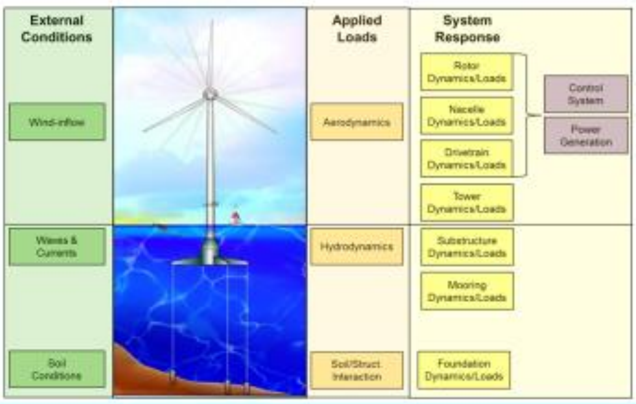
Findings from IEA Wind Task 30 "OC5" and Plans for OC6 - Focus on Hydrodynamics

Amy Robertson

September 6, 2017

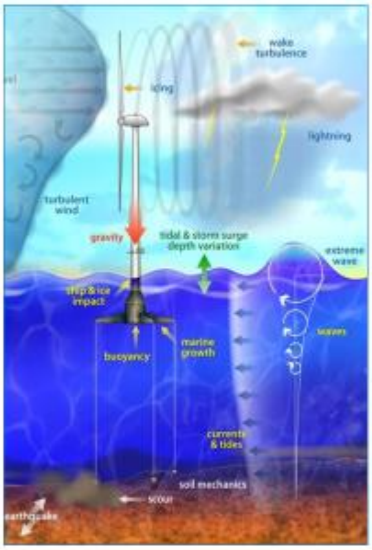
Background – Offshore Wind Modeling

For the design of *floating wind systems* and to better optimize *fixed-bottom offshore wind systems*, modeling tools are needed that consider the coupling between aerodynamic and hydrodynamic loading.



Background – Coupled Modeling Tools

- Coupled modeling tools for the design of offshore wind systems are ones that consider:
  - Aerodynamics
  - Hydrodynamics
  - Structural dynamics
  - Control of offshore wind systems.
- These tools were adapted from land-based wind modeling tools and offshore structural tools.
- Coupled design tools are relatively new and need to be verified/validated to ensure their accuracy and give confidence to the users.
- Examples:
  - **Wind:** FAST, Bladed, HAWC2
  - **Offshore:** OrcaFlex, Sesam, DeepLines, OPASS



IEA Wind Tasks 23 and 30 – OC3, OC4, OC5

- Three research projects were initiated under IEA Wind to address this issue: OC3, OC4, and OC5.

OC3 = Offshore Code Comparison Collaboration
OC4 = Offshore Code Comparison Collaboration, Continued
OC5 = Offshore Code Comparison Collaboration, Continued, with Correlation

- OC3 operated under IEA Wind Task 23 (2005-2013)
- OC4/OC5 operated under IEA Wind Task 30 (2014-2018)

OCx Objectives

- Assess simulation accuracy & reliability
- Train new analysts how to run codes correctly
- Investigate capabilities of implemented theories
- Improve modeling tools/methods
- Identify further R&D needs

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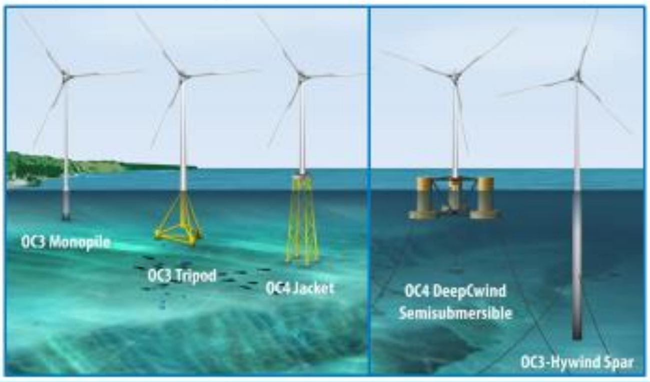
OC3/OC4

OC3/OC4 focused on *verification*

- Coupled modeling tools verified through code/code comparisons of simulations of fictional offshore wind systems in a variety of conditions
- Helped to identify errors in the tools and see influence of differences in modeling theories and approaches



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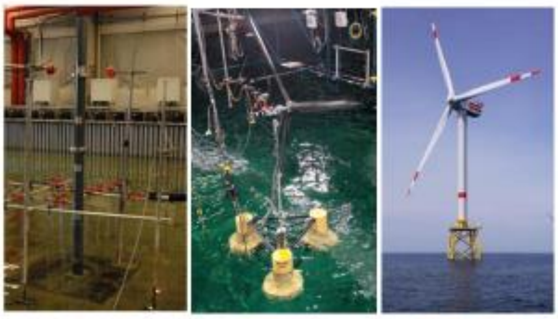
OC5

OC5 focuses on *validation*

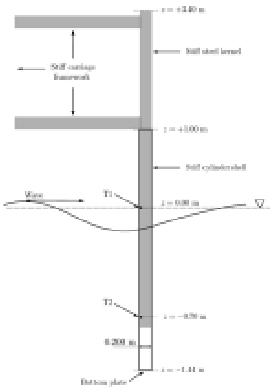
- Simulations from coupled modeling tools compared to measurements from a test campaign
- Results from different tools show advantages/disadvantages of modeling approaches
- Data was not generated in the project, but rather relied on shared data



Phase I	Phase II	Phase III
2014-2015	2015-2016	2017-2018

OC5 Phase Ia Takeaways

- **Phase Ia – Rigid Monopile**
  - Potential for a lot of variation in tuned hydrodynamic parameters - look-up tables can have different values
  - Best tuning approach was found to be weighted least-squares
  - For larger waves, important to have models that capture the 2nd and 3rd order harmonic force components
  - For larger k*R values, nonslender diffraction effects reduce 2nd harmonic forces in experimental data, compared to simulations
  - 3rd harmonic forces are key in prediction of ringing loads, under-predicted - especially for higher k*R values
  - Calculating loads up to the instantaneous wave elevation important in capturing 2nd harmonic force, more than higher-order potentials
  - Need at least 2nd order wave loads and calculation of the force up to the IWL to capture most of the 3rd harmonic force.



ISOPE 2015 Paper

OC5 Project Phase I: Validation of Hydrodynamic Loading on a Fixed Cylinder

OC5 Phase Ib Takeaways

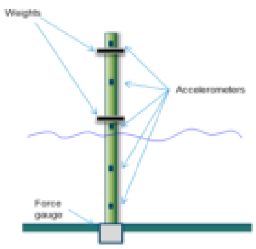
- **Phase Ib – Flexible Monopile**
  - Higher-order wave theory is important in capturing the higher-order components of the hydrodynamic force
  - Complexity of nonlinear wave transformation over a sloped seabed (for this case) has shown a potential need for higher-fidelity approaches to accurately model the wave kinematics
  - Tools do not presently capture total force applied to the structure during a breaking wave event – adding additional impulsive force?

Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia

13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway

OC5 Project Phase Ib: Validation of Hydrodynamic Loading on a Fixed, Flexible Cylinder for Offshore Wind Applications

Amy N. Robertson[a,*], Fabian Wendt[a], Jason M. Jonkman[a], Wojciech Popko[b], Michael Borg[c], Henrik Bredmose[c], Flemming Schlutter[c], Jacob Qvist[e], Roger Bergua[f], Rob Harries[g], Anders Yde[c], Tor Anders Nygaard[h], Jacobus Bernardus de Vaal[h], Luca Oggiano[h], Pauline Bozonnet[i], Ludovic Bouy[j], Carlos Barrera Sanchez[k], Raúl Guanche García[k], Erin E. Bachynski[l], Ying Tu[m], Ilmas Bayati[n], Friedemann Borisade[o], Hyunkyoung Shin[p], Tjeerd van der Zee[q], Matthieu Guerinel[r]



OC5 Phase II Takeaways

- **Phase II - Semisubmersible**
  - Under-prediction of both fatigue and ultimate loads both wave-only and wind/wave
  - Pitch natural frequency excitation in wave-only conditions significantly under-predicted by most
  - Dynamic mooring models needed to capture mooring loads (not necessary for sys. dynamics?)
  - Tower frequency excitation in wave-only over-predicted by ME (diffraction effects not captured)
  - No focus on aerodynamics, since differences in wave excitation dominated the differences
  - Uncertainty in the wind characteristics – broad-band frequency excitation of the system
  - Need to do a proper uncertainty assessment to determine differences between exp and sim
  - Need planned validation campaigns – modelers involved in tests, and modeling done before testing starts

Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia

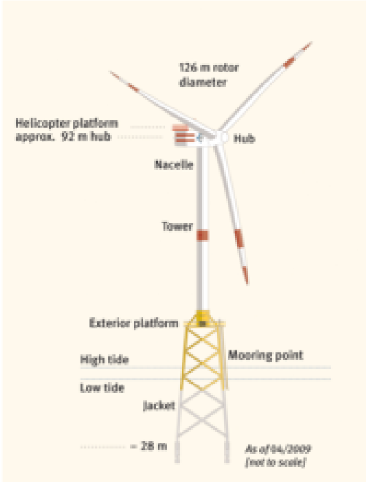
14th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2017, 18-20 January 2017, Trondheim, Norway

OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floating Semisubmersible Wind Turbine

Amy N. Robertson[a,*], Fabian Wendt[a], Jason M. Jonkman[a], Wojciech Popko[b], Habib Dagher[c], Sebastien Gueydon[d], Jacob Qvist[e], Felipe Vittori[f], José Azcona[f], Emre Uzunoglu[g], Carlos Guedes Soares[g], Rob Harries[h], Anders Yde[i], Christos Galinos[i], Koen Hermans[j], Jacobus Bernardus de Vaal[k], Pauline Bozonnet[l], Ludovic Bouy[m], Ilmas Bayati[n], Roger Bergua[o], Josean Galvan[p], Iñigo Mendikoa[p], Carlos Barrera Sanchez[q], Hyunkyoung Shin[r], Sho Oh[s], Climent Molins[t], Yannick Debruyne[u]

OC5 Phase III Takeaways

- **Phase III – Jacket – Full-Scale**
  - On-going
  - IP issues can definitely be difficult to contend with, and may limit the fidelity of the data that you receive
  - Examining a full scale system has different characteristics than model scale systems – and our ability to model them will change (needed)
  - High uncertainty in open ocean tests – no controlled environment and difficult to measure – relegated to more statistical-type analyses



OC6 Topic Areas

- Goals of this meeting are to:
  - Determine objectives of OC6
  - Determine how to integrate with other tasks on aerodynamics and farm-level analysis
  - What the 6^{th} "C" is
- OC6 objective ideas:
  - More in-depth focus on hydrodynamics and aerodynamics individually
  - Integrate higher-fidelity modeling (3-Way Validation)
  - Uncertainty assessment
  - Own testing
    - Focus on specific phenomena
  - Simplified testing (component-level, hybrid, etc.)
  - New design concepts

PIRT – Phenomena Identification Ranking Table

- What are the phenomena in the modeling that we do not fully understand?
- Focus validation campaign on answering specific issues
  - EX: Low-frequency excitation in wave-only conditions

Phenomena	Importance	Physics Und.	Model Adequacy	Validation Needs
Fluid Dynamics				
Breaking/steep waves				
Multi-body flow interaction				
Hydro-elasticity				
Nonlinear excitation – diff/sum/mean	High	Medium	Medium	High
Breaking/steep wave loads				
VIV	Low	Medium	Low	Low
Change in hydro coeffs for different wave frequencies				
Loads affected by structure loc. in flow				
Springing (TLP)				
Wave-induced internal loads in support structure				
Influence of structural flexibility and compliance of components on loads				
Controls				
Negative damping from blade pitching	High	High	High	Low
Moorings				
Seabed friction – mooring loads				
Wave forcing – mooring loads				

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Validation Phenomena

- Nonlinear excitation of frequencies from waves
  - Difference and sum (high and low)
  - Mean offset
- Breaking wave and/or steep wave response
- Change in hydrodynamic coefficients for different wave frequencies
- VIV
- Negative damping from blade pitching
- Wind damping characteristics
- Variation in hydrodynamic loading for a still body versus one that moves in flow field (location not velocity influence)
- Moorings

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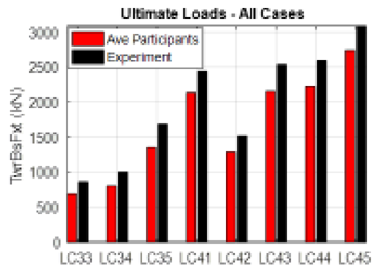
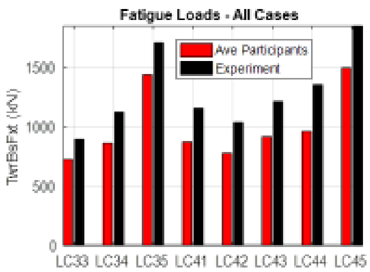
Data for OC6

- **Coordination with other validation tasks:**
  - Consider looking at aerodynamics separately and coordinate with those interested in land-based wind validation
  - Participants of OC5 could potentially participate in a new research task in this area
  - Or, OC6 could create a WP focused on aerodynamic force validation only, and invite others to join
- **Our own testing:**
  - Would like to pursue developing our own datasets
  - MaRINET2
  - Lower-cost UMaine W2 or similar research tank
- **Other datasets:**
  - Nautilus – semisubmersible – Tank Test – Jan 2018
  - Stiesdal TetraSpar – 3 Tank Tests
- **Suggestions?**
  - System to test in MaRINET2?

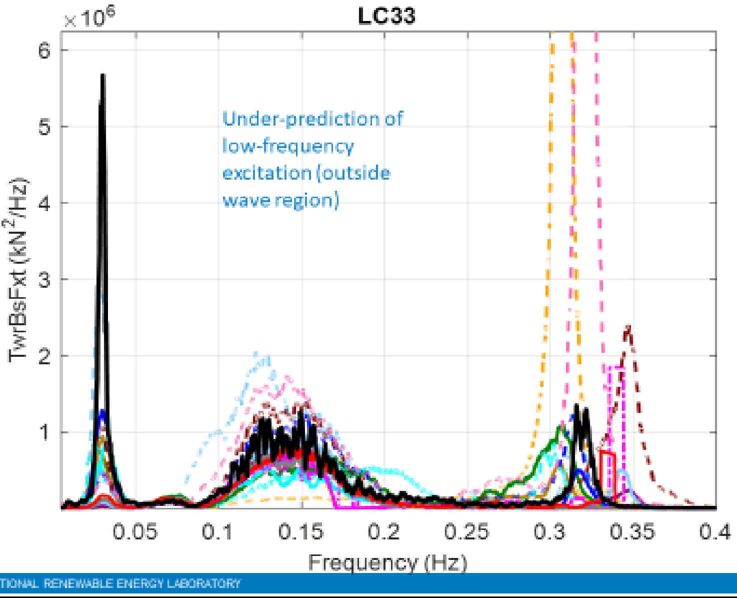
MARINET2

- Received funding to do 1 week of testing at MARIN this fall (just tank test time covered)
- Testing of OC5 semisubmersible without turbine (wave-only)
- Focus of tests is to try to determine reason for differences seen between tests and simulations in Phase II of OC5





OC5 Modeling Issues



6th "C" for "OC6"

- Offshore Code Comparison Collaboration
  - Continued
  - with Correlation

  - and unCertainty
  - and Certainty
  - and Computations
  - and CFD
  - and Co-validation


Thank You!

Findings from IEA Wind Task 29 "Mexnext" and Plans for Use of the DANAERO Database in an IEA Task 29 extension

Helge Aagaard Madsen, DTU and Gerard Schepers, ECN

IEA Wind task 11 - Topical Expert Meeting #88 - 6th-8th of September in Scotland

IEA Wind Task 29 - Status and proposal for extension using the DANAERO data base

History

Since 1991, IEA has played a very important role in aerodynamic model improvement

- 1991-1997: IEA Task 14 (Field Rotor Aerodynamics)
- 1997-2001: IEA Task 18 (Field Rotor Aerodynamics, enhanced)
- 2001-2007: IEA Task 20: (NREL Phase VI, NASA-Ames wind tunnel measurements
- 2008-2017: IEA Task 29: Phases 1 to 3 ((New) Mexico wind tunnel measurements)

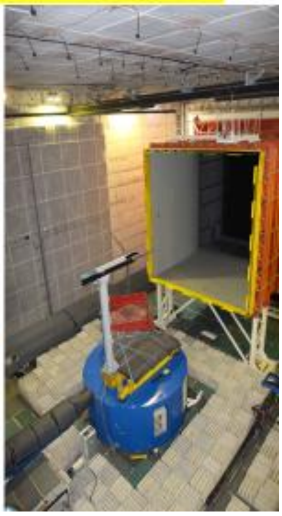
IEA Wind Task 29 - Status and proposal for extension using the DANAERO data base

Mexico and New-Mexico

- Mexico = Model rotor EXperiments In COntrolled conditions
- Collaborative projects, coordinated by ECN
  - Mexico: December 2006
  - New Mexico: July 2014
- Measurements in Large Low Speed Facility (LLF) of German Dutch Wind tunnel (DNW)
  - Open test section: 9.5 x 9.5 m^2
  - Diameter of rotor: 4.5 m
  - 3 blade turbine

New MEXICO: Instrumentation and apparatus

- 6-Component DNW balance @ tower foot (time averaged force including nacelle and tower contribution)
- Tunnel measurements: freestream velocity (re-calibrated), collector pressures, temperature
- 1P sensor (renewed by DNW)
- Blade root strain gauges (renewed by ECN)
- PIV (sheet size from 337x394mm -> 380x610mm)
- ABB signals: generator torque and HSS rpm
- Acoustics: far field mics and microphone array
- Blade pitch angle, accelerometer and inclinometer
- Blade unsteady pressure sensors (calibrated)



New Mexico (Test matrix)

Test type		Velocity verifica-tion	Loads vs velocity	Standstill	Axial flow (pressure)	PIV	Dynamic inflow	Yawed flow (pressure)	Blade add-ons	Pitch misalign-ment	Flowviz	Blade-off
Apparatus	DEMO Balance	x x	x x	x x	x x	x x	x x	x x	x x	x x	(x) x	(x) x
	PIV traverse	(+ pitot) radial	axial radial			axial radial						
	Mics Array	x x	x x	x x	x x	x x	x x	x x	x x	x x	x x	x x
Model config'		0	0	0, 3	3	3	3	3	1, 2, 4, 5	3, 6	7	99
Operational condition	Pitch angle [°]	90	-5.3→1.7	-2.3→90	-5.3→1.7	-2.3	-2.3 Steps	-2.3,0.7	-5.3→1.7	-5.3→-20	-2.3, 73.6	NA
	Yaw angle [°]	0	0	-90→+30	0	-30,0,30	0,15,30	-30→+45	0	0	0	-30→+30
	Rot. speed [rpm]	0	324,424	0	324,424	424	324,424 Ramp	424	0,324,424	324	0,324,424	0,324,424
	U_∞ [m/s]	10→30	7.5→24	30	5→30	10,15,24	10,15,18	10,15,18,24	5→30	5→15	15,18,30	10→30

New Mexico (Configurations)

Legend number	Configuration
0	Roughness on full blade
1	Guerney flaps long
2	Guerney flaps short
3	Outboard blade clean
4	Spoilers
5	Serrations
6	Pitch misalignment B2 (-20°)
7	Oil flow: sensors taped off
99	Blade off

Correlation of experiment with the axial momentum theory

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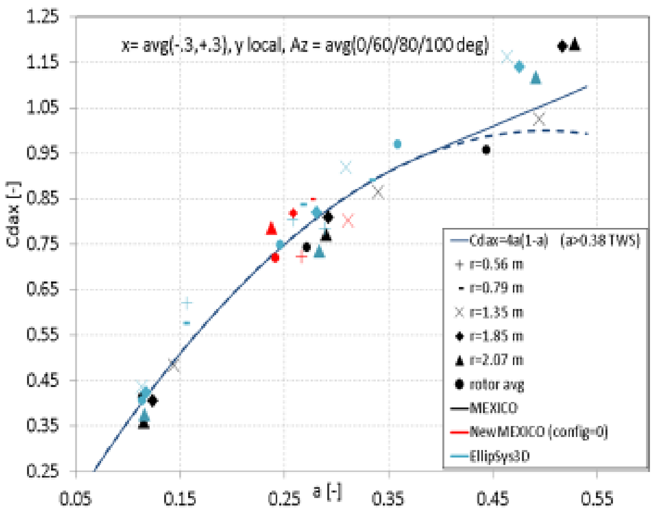


First round of calculations: Selected cases

ECN

Case	V_{tunnel} [m/s]	Pitch angle [deg]	Ω [rpm]	ρ [kg/m³]	Yaw angle [°]	p_{ref} N/m²	AOA @80%R approx [deg]	a_axial @80%R approx [-]
1.1	10.05	-2.3	425.1	1.197	0.0	101398	3.0	0.50
1.2	15.06	-2.3	425.1	1.191	0.0	101345	7.0	0.30
1.3	24.05	-2.3	425.1	1.195	0.0	101407	14.0	0.13

8

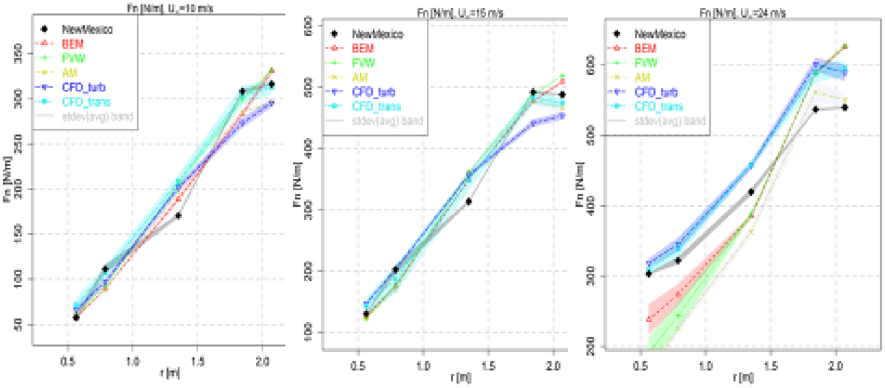
First round of calculations:

Participants code/model characteristics

- DLR: Tau, CFD
- DNV-GL: BEM, VL
- DTU: EllipSys3D CFD, HAWC2, AL
- ECN: ECNAero BEM
- IFE: CFD
- Onera: ElsA, PUMA
- Suzlon: BEM
- Technion: BEM (, CFD)
- Uppsala: CFD, AD
- USTUTT: Flower, CFD with AL/full and URANS

New Mexico (Mexnext loads validation)

- Axial flow, 425 rpm, pitch=-2.3deg



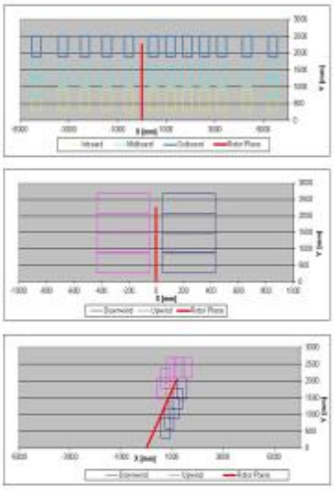
Turbulent Wake State
λ=10.0

Design conditions
λ=6.7

Separated flow
λ=4.2

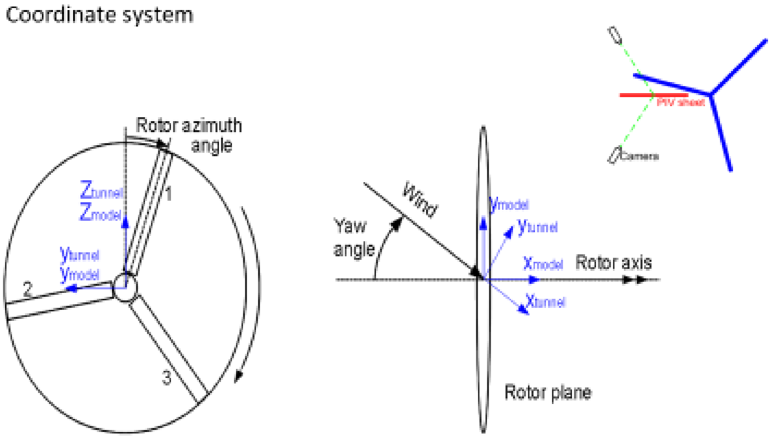
New Mexico (PIV overview)

U_∞ [m/s]		15	10	15	24
Rot. speed [rpm]		424	424	424	424
Pitch angle [°]		-2.3	-2.3	-2.3	-2.3
Blade config	(Table 3)	0	3	3	3
Axial flow	Axial	x	x		x
	Radial	x	x	x†	x
	Momentum			x	
Yawed flow (+/-30°)	Axial			x	
	Radial		x	x	x‡



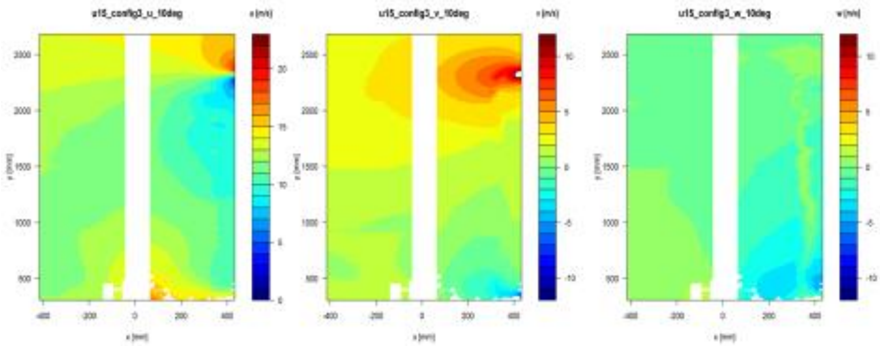
New MEXICO (PIV)

- Coordinate system



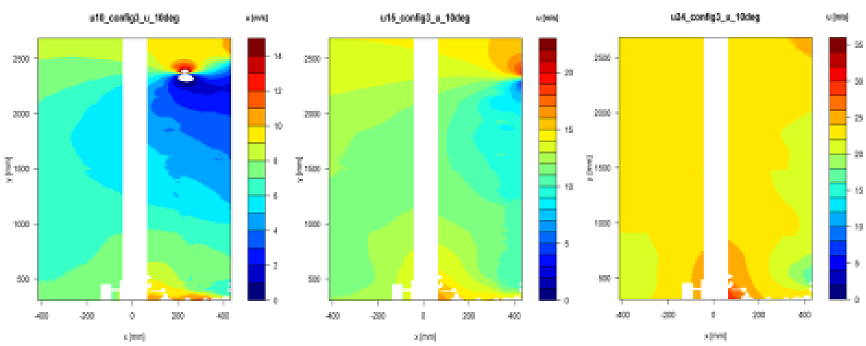
New Mexico (PIV)

- Radial traverse 15m/s, config=3 - u, v, w



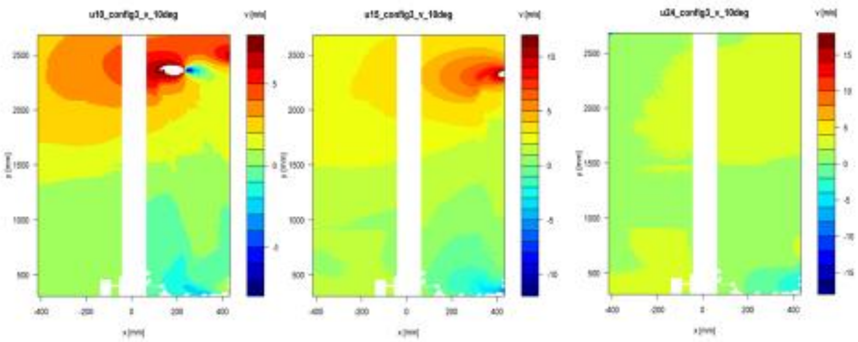
New Mexico (PIV)

- Difference between 10, 15 and 24 m/s - u

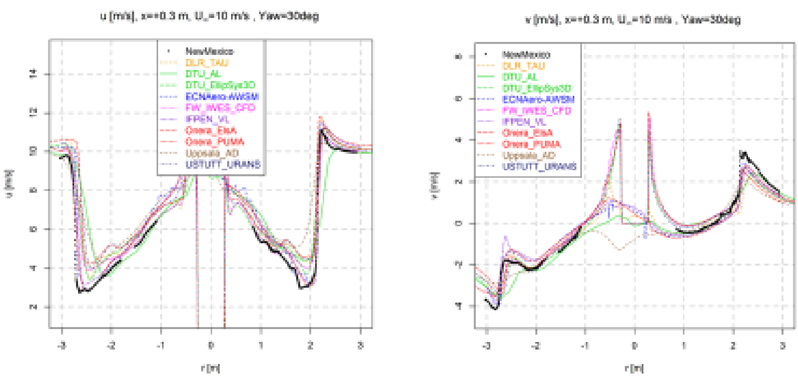


New Mexico (PIV)

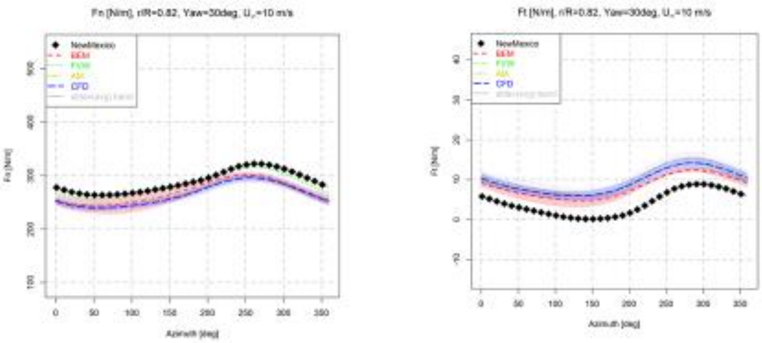
- Difference between 10, 15 and 24 m/s - v



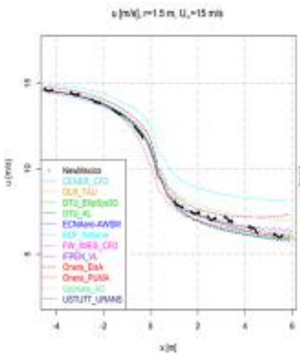
New Mexico (PIV) – operation at 30 deg. yaw



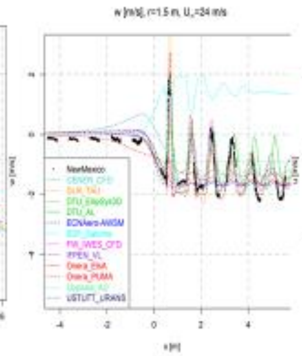
Loads – operation at 30 deg. yaw



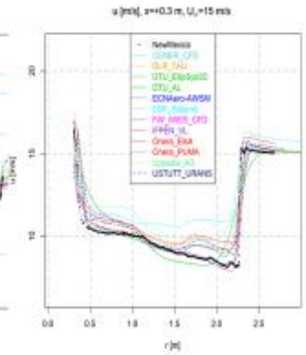
New Mexico (Mexnext velocity validation)



Axial traverse of u at r=1.5m
Design conditions
λ=6.7



Axial traverse of w at r=1.5m
Separated flow conditions
λ=4.2



Radial traverse of u at x=0.3m
Design conditions
λ=6.7

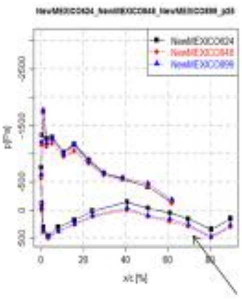
ECN

New Mexico (Guerney flaps)

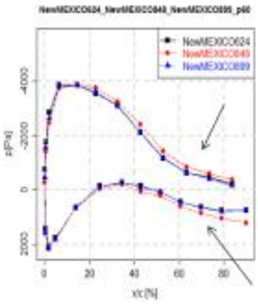
- Effect of Guerney flaps

(red up r/R<0.6, blue r/R<0.46)

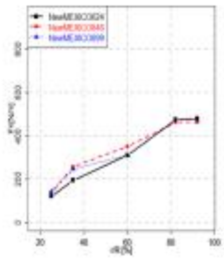
Guerney flap geometry



25%R pressure distribution



60%R pressure distribution



normal force distribution

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Synergies with Tasks, TCPs & Others

- Task 19: "Wind Energy in Cold Climates" (effect of aerodynamics on iced turbine blades)
- Task 28: "Social Acceptance of wind energy projects" (Acoustics)
- Task 30 "Comparison of Dynamic Computer Codes and Models for Offshore Wind Energy" (partly aerodynamic driven)
- Task 31, "Wakebench" (far wake determined by near wake)
- Task 37 "Wind Energy Systems Engineering: Integrated R, D&D" (partly aerodynamic driven)
- Task 38 "Quiet noise technologies" (Acoustics)

Appendix A: (New) Mexico data delivered to:

ECN

1. University of Liverpool (UK)
2. Forth (Greece)
3. University of Hamburg (Germany)
4. Lund University (Sweden)
5. University of Wyoming (USA)
6. University of Louvain (Belgium)
7. University of Darmstad (Germany)
8. ETH Zurich (Switzerland)
9. Oxford University (UK)
10. University of Californie (USA)
11. University of Naples, Frederico II (Italy)
12. University of Michigan (USA)

Notice: The IEA Wind agreement, also known as the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems, functions within a framework created by the International Energy Agency (IEA). Views, findings and publications of IEA Wind do not necessarily represent the views or policies of the IEA Secretariat or of all its individual member countries.

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Appendix A: (New) Mexico data delivered to:

ECN

13. University of Tennessee at Chattanoog (USA)
14. Pennsylvania State University (USA)
15. Hitachi (Japan)
16. FluiDyna (Germany)
17. University of Malta (Malta)
18. RWTH Aachen University (Germany)
19. TU Berlin (Germany)
20. University of Central Lancashire (UK)
21. Chalmers University (Sweden)
22. Engys (UK)
23. VUB (Belgium)
24. University of Massachusets (USA)

Notice: The IEA Wind agreement, also known as the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems, functions within a framework created by the International Energy Agency (IEA). Views, findings and publications of IEA Wind do not necessarily represent the views or policies of the IEA Secretariat or of all its individual member countries.

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Appendix A: (New) Mexico data delivered to:

25. Shahrood University of Technology (Iran)
26. Universidad Politecnica de Catalanio- CTTC (Spain)
27. UAS Windesheim (NL)
28. Arizona State University (USA)
29. KTH Stockholm (Sweden)
30. ETS Montreal (Canada)
31. Research Center of Computational Mechanics, Inc, Tokishi, Tokyo, Japan
32. University of Botswana, Botswana
33. Suzlon Denmark
34. Pensylviana State University, USA
35. Korea Advanced Institute of Science and Technology (KAIST)
36. Duke University, USA

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Conclusions from the last IEA Task 29 Meeting at ONERA, Nov. 2016

Consensus to continue because

1. Important outcomes:
    - Better agreement between calculations and measurements
        - Recommendations on how to use aerodynamic models in design codes
        - IEC Aerodynamics
    - Measurement knowledge
    - Validation platform
2. Aerodynamics is not finished
    - Aerodynamics for 10MW+ wind turbines in inflow conditions is a particular challenge
3. Pure scientific and technical focus on wind turbine aerodynamics
4. Cooperation between continents

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Project Meeting ONERA, ctd

Consensus to continue because

- New measurements are expected to become (publicly) available
  - DANAERO (detailed aerodynamic **field** measurements on NM80 turbine)
- Good aerodynamic measurement data in wind energy society are still far too limited (as stated by subgroup aerodynamics of EERA and research agenda of European Academy of Wind Energy)

Background for initiation of the DANAERO project in 2007

- **Field rotor experiments in the period from 1987-1993 –- IEA Annexes XIV and XVIII**
  - NREL (US), Risoe (DK), ECN (NL), DELFT (NL), MIE Univ. (Japan), Imperial College (UK)
- **NREL Unsteady Aerodynamics Experiment (UAE) on a 10 m diameter rotor in the NASA Ames 80 foot by 120 foot in year 2000 –- IEA Annex XX**
- **MEXICO experiment in 2006 in DNW 9.5 m x 9.5 m wind tunnel on a 4.5 m diameter rotor – IEA Annex 29**

Shortcomings of old data sets

- Blade and rotor designs not representative for modern MW rotors
- No influence of **shear** and **atmospheric turbulence** in the inflow to the rotor not present in the wind tunnel experiments
- No operation in wakes
- Low Reynolds number
- No influence of control actions, e.g. variable speed and blade pitch

Objectives of the project

Provide experimental data that can be used for investigations of:

- correlation between 2D and 3D airfoil characteristics
- boundary layer transition characteristics in 2D wind tunnel flow environment compared with full scale 3D rotor flow transition characteristics
- inflow characteristics (shear and turbulence) on MW rotors with particular focus on the high frequency content
- dynamic induction characteristics
- wake flow characteristics
- pressure fluctuations in the boundary layer influencing turbulent inflow noise and trailing edge noise

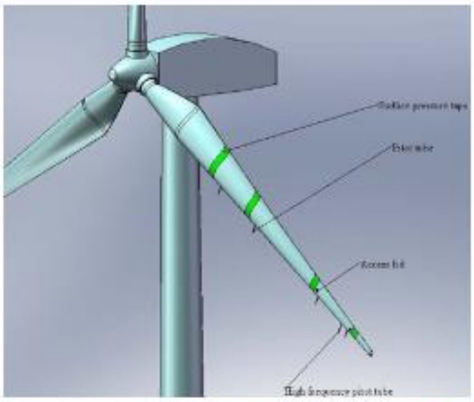
The DANAERO MW experiments

Carried out in collaboration between DTU the industrial partners **Vestas**, **Siemens**, **LM** and **DONG Energy** from (2007-2010) and (2010-2013) in projects funded by EUDP in Denmark:

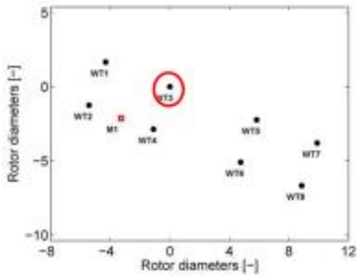
1. Wind tunnel tests of airfoils in three different wind tunnels –- LM, Velux and Delft
2. Measurement of inflow characteristics on a MW wind turbine at the Hoevsoere test site – the Siemens 3.6 MW turbine
3. **Measurement of blade surface pressure and inflow on a MW turbine in the small Tjaereborg wind farm in Jutland – NM80 2MW turbine**

Pressure and inflow measurements on the NM80 turbine in the Tjaereborg wind farm

- surface pressure and inflow measured at 4 radial stations
- the outboard station also instrumented with around 60 microphones for high frequency surface pressure measurements
- high frequency measurements of the inflow
- measurements from June to September 2009



The DANAERO experiments were carried out on a NM80 turbine in the Tjaereborg wind farm



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A new LM 38.8m test blade was manufactured, instrumented and installed

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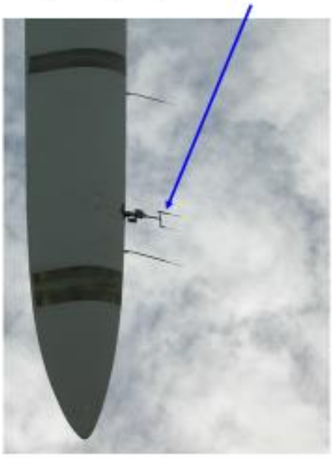
Pressure and inflow measurements on the NM80 turbine in the Tjaereborg wind farm



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Measured pressure distributions in comparison with EllipSys3D simulations

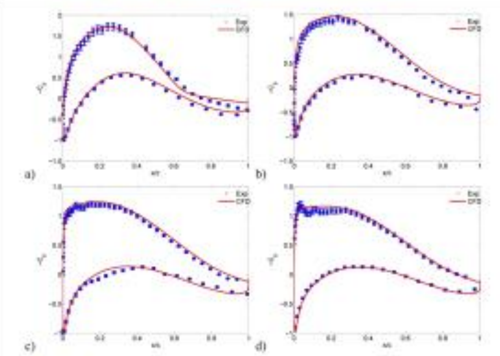

Figure 9.4. Comparison of measured and computed C_p distributions on the NM80 turbine operating at $V_\infty = 6.1 ms^{-1}$ at a rotational speed of 12.1 RPM and a pitch angle of 0.15°. a) r/R=0.325; b) r/R=0.475; c) r/R=0.750; d) r/R=0.925.

From final report DANAERO II report

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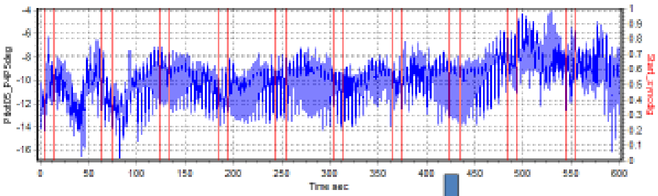
Transition: yawed operation at 60deg
14:40, 19/8, 2009



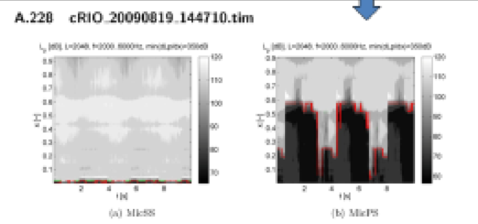


Figure 228. cRIO_20090819_144710.tim

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Recent results from the AVATAR project
- turbine operating at 6.1 m/s

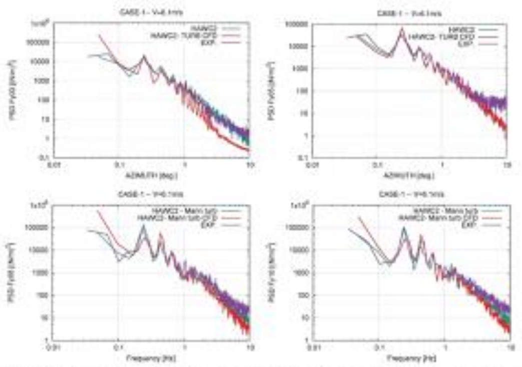

Figure 116: Comparison of PSD of measured and simulated aerodynamic forces Fy perpendicular to the chord at four radial positions.

IEA Wind Task 29 - Status and proposal for extension using the DANAERO data base

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Work Packages (Preliminary)

WP1: Establishing the DANAERO data base

WP2: Comparison of simulations with selected DANAERO cases

- Aerodynamics, aero-elastics, aero-acoustics

WP3: Detailed analysis

- Aerodynamic response to turbulent inflow
- Sheared and yawed inflow
- 2D/3D airfoil characteristics
- Aeroelastic effects
- Wake flow operation
- Transition characteristics in realistic flow conditions
- Characterization of noise sources by high frequency surface pressure measurements
- Standstill

WP4: Synthesis of results/observations from present and previous IEA Task 29 work

Management issues

- OA: ECN with contribution from DTU
- Anticipated countries
  - Netherlands, Denmark, Germany, France, USA, China, Spain, Sweden, Norway
  - Interest expressed from Italy, Greece, Israel
  - Who else?

IEA Wind Task 29 - Status and proposal for extension using the DANAERO data base

CENER CENTRO NACIONAL DE ENERGÍAS RENOVABLES

IEA Task 31 "Wakebench" V&V Framework for Wind Farm Flow Models: Towards Phase 3

Javier Sanz Rodrigo

IEA TEM#88, Edinburg, 6 September 2017

IEA Wind Task 31 Wakebench

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IEA Task 31 "Wakebench": Objectives

- To improve wind farm modeling techniques and provide a forum for industrial, governmental and academic partners to develop, evaluate and improve atmospheric boundary layer and wind turbine wake models for use in wind energy
  - ❑ from flat to complex terrain,
  - ❑ from single to multiple wakes,
  - ❑ from near to far wake,
  - ❑ from mesoscale to microscale,
  - ❑ both onshore and offshore,
  - ❑ using well defined test cases from the literature and test wind farms ("research" conditions) as well as from industrial sites ("real-life" conditions)

Phase 1 (2011-2014)
Phase 2 (2015-2018)

- To build consensus on flow model evaluation procedures, including uncertainty quantification

… same as Task 31 phase 1, wider scope in phase 2

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Task Structure and Deliverables

WP0: Management and Coordination (CENER)	**ExCo Reports**
WP1: Benchmarking from mesoscale to microscale models (CENER) Task 1.1: Setting-up of the benchmark platform for mesoscale models Task 1.2: Definition of validation procedures for mesoscale models Task 1.3: Definition of benchmarks and scheduling for "wind" models	**Windbench.net** • Inventory of models • Repository of benchmarks
WP2: Benchmarking from near-wake to wind farm array models (NREL) Task 2.1: Set-up the benchmark platform for wind tunnel models Task 2.2: Definition of validation procedures using wind tunnel experiments Task 2.3: Definition of validation procedures using lidar experiments Task 2.4: Definition of benchmarks and scheduling for "wake" models	
WP3: VV&UQ framework and user guidelines (SNL) Task 3.1: Review of UQ methods and integration on a VV&UQ framework Task 3.2: Best practice procedures	**2nd edition of MEP + BPG**

Formal deliverables:
Model Evaluation Protocol (MEP)
Best Practice Guidelines (BPG)

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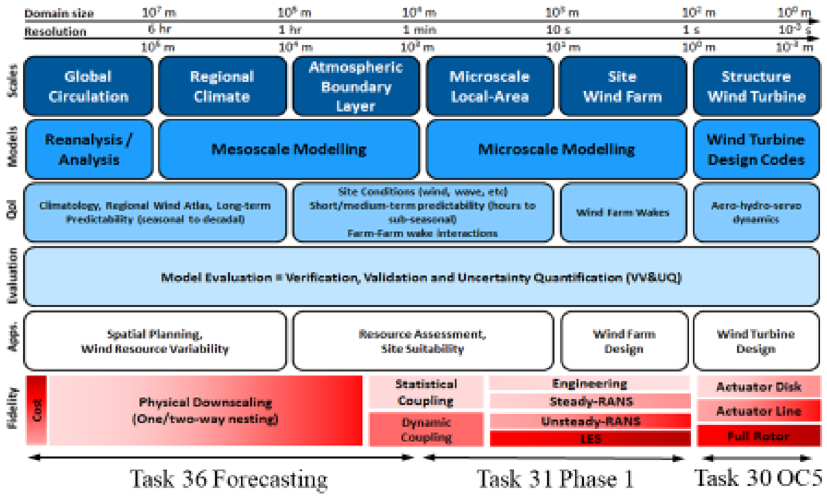
Modeling Scope



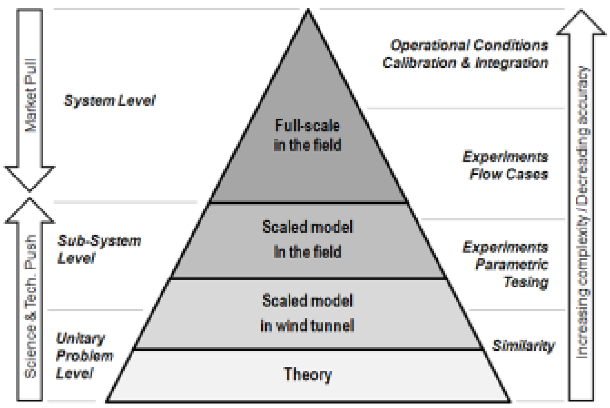
Expected Outcome

- Extend modeling scope from **Phase 1**, “microscale”, to **Phase 2**: “meso-micro” and “near-wake”
- Greater focus on reducing the spread using high quality experiments and evaluation procedures
- Uncertainty Quantification added to the Wakebench Model Evaluation Protocol (MEP)
- Unified validation strategy (built from Ae2 and NEWA projects) that can be further executed into **Phase 3**

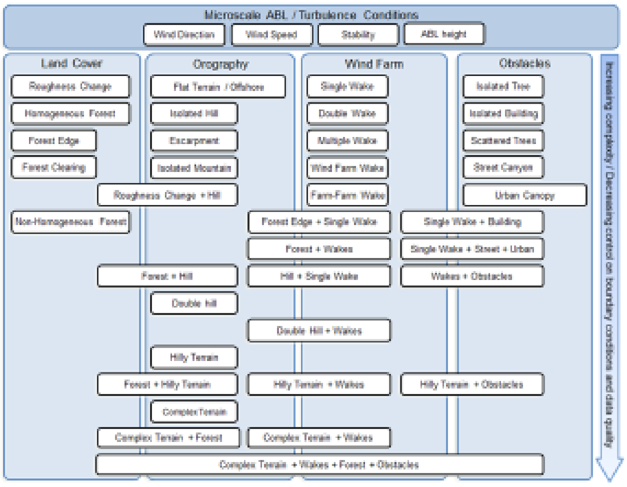
Model Evaluation Protocol (MEP): V&V strategy

- Whatever model we develop it will be as good as the validation data it is based upon
- Validation Objectives
  - ❑ Identify **relevant physics** that the model should incorporate
  - ❑ Define a **targeted validation strategy** to determine how the model is succesfull at incorporating those phenomena (subsystem validation)
  - ❑ Understand where are the **knowledge gaps**
  - ❑ Evaluate the model at system level to assess the **impact** of these gaps in the **quantities of interest**
  - ❑ Categorize performance **metrics** in terms of site and wind climate conditions
- Adopt a formal verification and validation (V&V) framework adapted to the specific needs of our application
  - ❑ Identify **end-user requirements** in terms of target quantities of interest
  - ❑ Identify **modeling scope** that will meet the end-user requirements
  - ❑ Define **fit-to-purpose metrics**
  - ❑ **Provide orientation** on how to best use the model in terms of its validation range

Building-Block Validation Approach



Wakebench Phase 1: “Microscale” WF-scale building blocks

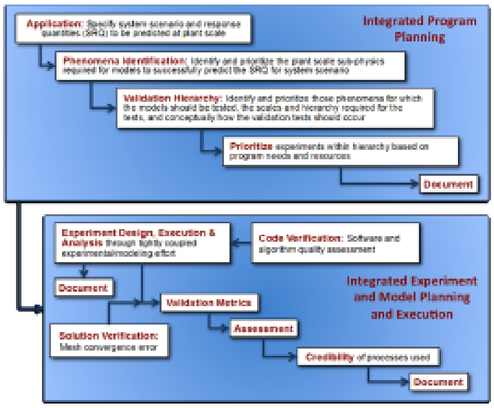


Phase 1 Repository of Validation Cases (Windbench.net)

	EXP Type			SCALE			RANGE		Stability		REGIME		LAND COVER						OROGRAPHY								WIND FARM					OBSTACLES				
Benchmark ID	Theory	Laboratory	Field	Microscale	Mesoscale	Meso-micro	Surface Layer	ABL	Neutral	Stratified	Steady	Unsteady	Homogeneous roughness	Roughness Change	Homogeneous Forest	Forest Edge	Forest Clearing	Non-homogeneous Forest	Flat Terrain	Offshore	Isolated Hill	Escarpment	Isolated Mountain	Double Hill	Hilly Terrain	Complex Terrain	Single Wake	Double Wake	Multiple Wake	Wind Farm Wake	Farm-Farm Wake	Isolated Tree	Isolated Building	Scattered Trees	Street Canyon	Urban Canopy
Alaiz_Neutral			x	x				x	x		x				x	x										x										
Alaiz_Sensitivity			x	x				x	x		x		x		x	x										x										
Askervein_Neutral			x	x			x		x		x		x								x				x											
AxisymmetricWake_Neutral	x	x		x			x		x		x		x						x																	
Bolund_Neutral			x	x			x		x		x			x							x	x														
Furry Hill_Neutral		x		x			x		x		x				x						x															
HornsRev_Neutral			x	x				x	x		x		x							x									x							
HornsRev_Stratified			x	x				x		x	x		x							x									x							
HornsRev_Turbulence			x	x				x	x		x		x							x									x							
HornsRev_Spacing			x	x				x	x		x		x							x									x							
InfiniteWindFarm_Neutral	x			x			x		x		x		x						x										x							
Leipzig_Neutral			x	x				x	x		x		x						x																	
Leipzig_Stratified			x	x				x		x	x		x						x																	
Lillgrund_360Efficiency			x	x				x	x		x		x							x									x							
Lillgrund_Direction			x	x				x	x		x		x							x									x							
Lillgrund_TISpacing			x	x				x	x		x		x							x									x							
MoninObukhov_Neutral	x			x			x		x		x		x						x																	
MoninObukhov_Stratified	x			x			x			x	x		x						x																	
NorrekaerEnge_DataQualification			x	x			x		x		x		x						x										x							
NorrekaerEnge_PowerDeficit1			x	x			x		x		x		x						x										x							
NorrekaerEnge_PowerDeficit2			x	x			x		x		x		x						x										x							
RisoWakeLidar_SingleWake			x	x			x			x	x		x						x								x									
SanGregorio_FreeFlow			x	x			x		x		x		x													x										
SanGregorio_Wakes			x	x			x		x		x		x													x			x							
Sexbierum_SingleWakeNeutral			x	x			x		x		x		x						x								x									
Sexbierum_DoubleWakeNeutral			x	x			x		x		x		x						x									x								
WavingWheat_Neutral		x		x			x		x		x		x						x																	

Phase 2: V&V Framework

- **Full system validation** of wind energy systems **is not possible**
- Need for a **planning process that prioritizes the phenomena** and a validation hierarchy with the largest impact on improving the predictive capacity of the models
- **Adopted in A2e and NEWA projects, unified in Wakebench**



Hills R.G., Maniaci D.C., Naughton J.W. V&V Framework. SANDIA Report SAND2015-7456, September 2015

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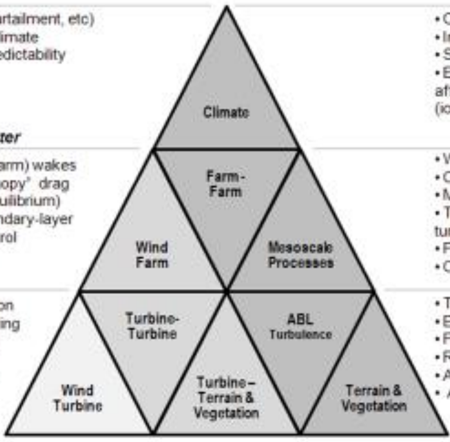
Phase 2: "Multiscale" building blocks

Power System
- Grid control (curtailment, etc)
- Feedback on climate
- Wind power predictability

Wind Farm Cluster
- Cluster (farm-farm) wakes
- Wind farm "canopy" drag
- Deep-array (equilibrium)
- Wind farm boundary-layer
- Wind farm control
- Far-wake

Wind Farm
- Wake interaction
- Wake meandering
- Turbine control
- Near-wake
- Fluid-structure interaction

Turbine



Climate
- Climate change
- Interannual variability
- Seasonal variability
- Environmental factors affecting performance (icing, dust, etc)

Mesoscale
- Weather events
- Coastal/mountains
- Meso-micro forcing
- Terra-incognita turbulence
- Free-atmosphere
- Coriolis

Microscale
- Terrain flow-separation
- Elevation changes
- Forest canopy
- Roughness changes
- Atmospheric stability
- Air-sea interaction

Surface-layer

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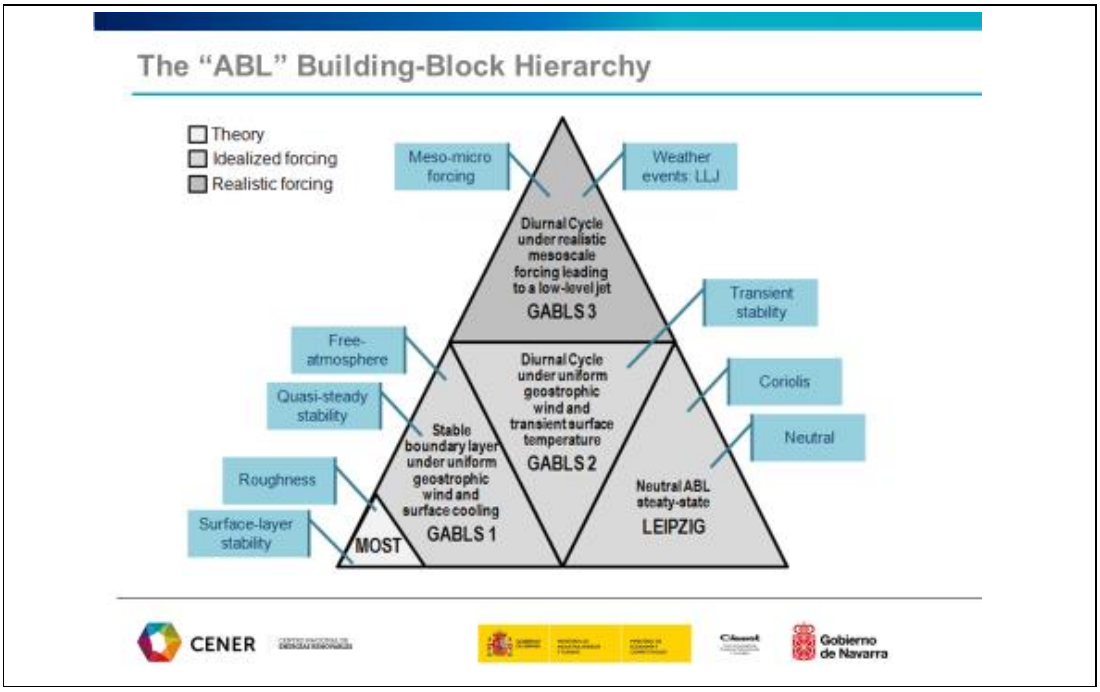
The "ABL" Building-Block Hierarchy
Theory
Idealized forcing
Realistic forcing
Meso-micro forcing
Weather events: LLJ
Diurnal Cycle under realistic mesoscale forcing leading to a low-level jet
GABLS 3
Transient stability
Free-atmosphere
Quasi-steady stability
Diurnal Cycle under uniform geostrophic wind and transient surface temperature
GABLS 2
Coriolis
Neutral
Stable boundary layer under uniform geostrophic wind and surface cooling
GABLS 1
Roughness
Surface-layer stability
MOST
Neutral ABL steaty-state
LEIPZIG
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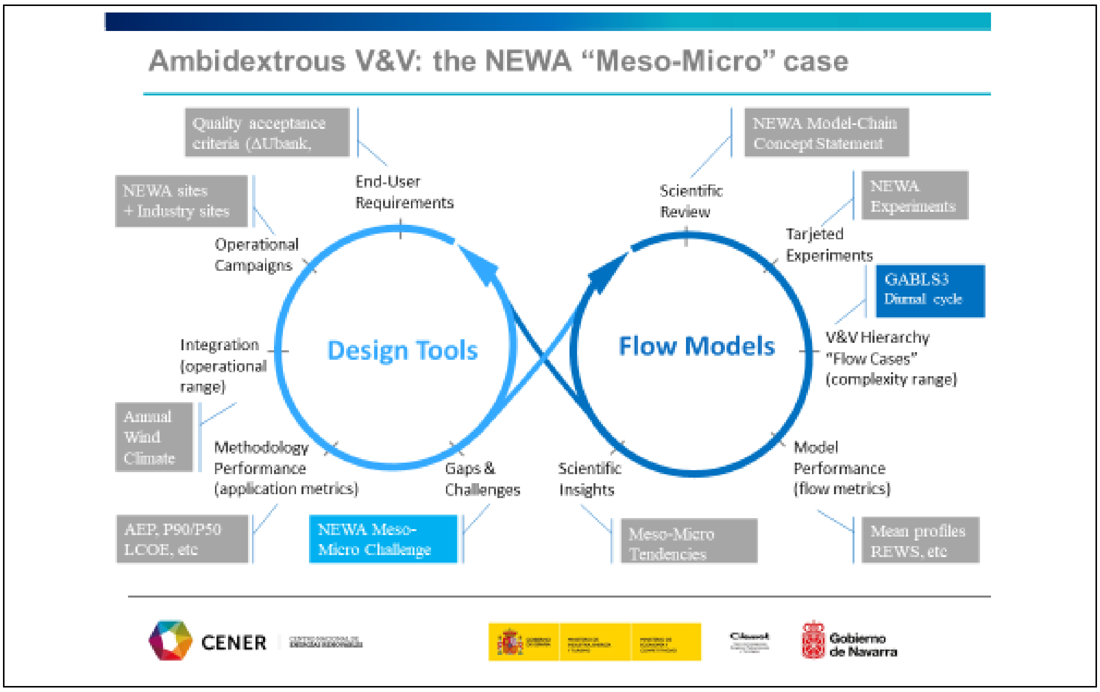
Ambidextrous V&V: the NEWA "Meso-Micro" case
Quality acceptance criteria (ΔUbank,
NEWA Model-Chain Concept Statement
NEWA sites + Industry sites
End-User Requirements
Scientific Review
NEWA Experiments
Operational Campaigns
Tarjeted Experiments
GABLS3 Diurnal cycle
Design Tools
Flow Models
Integration (operational range)
V&V Hierarchy "Flow Cases" (complexity range)
Annual Wind Climate
Methodology Performance (application metrics)
Gaps & Challenges
Scientific Insights
Model Performance (flow metrics)
AEP, P90/P50 LCOE, etc
NEWA Meso-Micro Challenge
Meso-Micro Tendencies
Mean profiles REWS, etc
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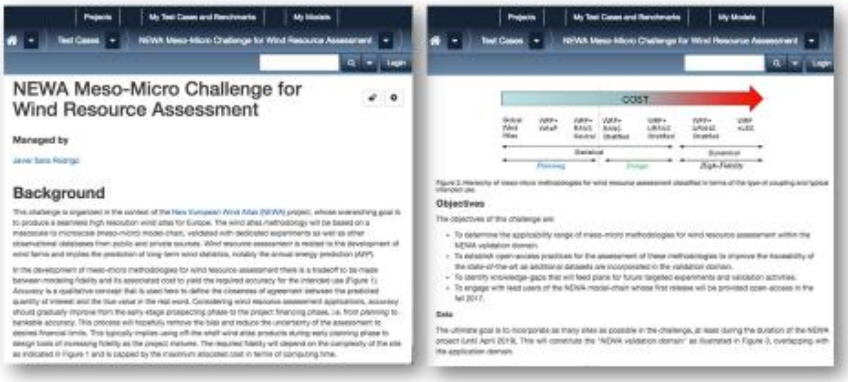
NEWA Meso-Micro Challenge



http://windbench.net/newa-meso-micro-challenge-wind-resource-assessment

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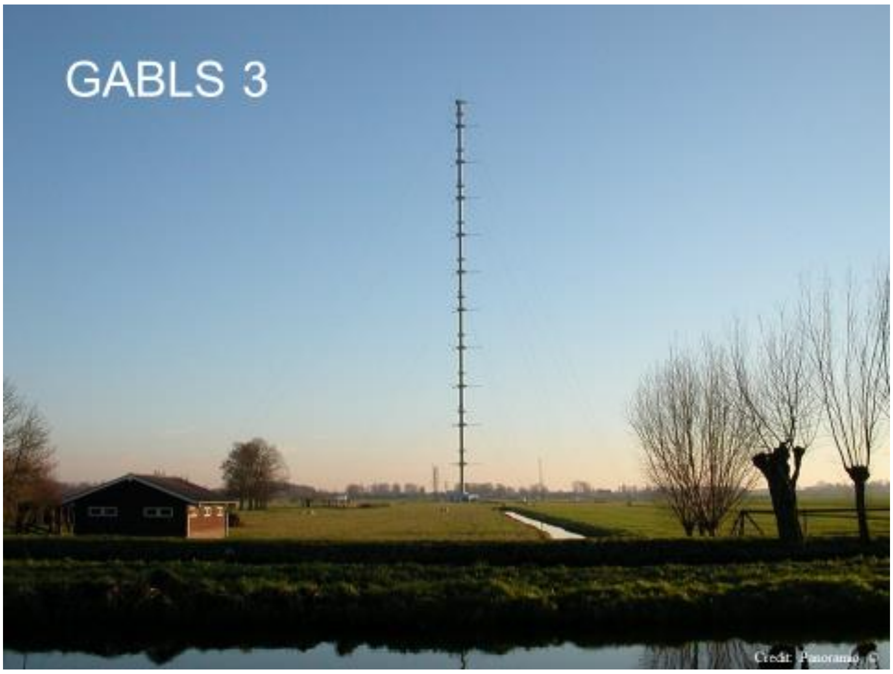
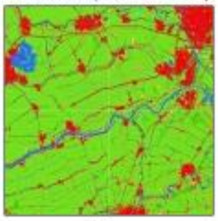


GABLS 3: Boundary-layer characteristics (Bosveld et al., 2014)

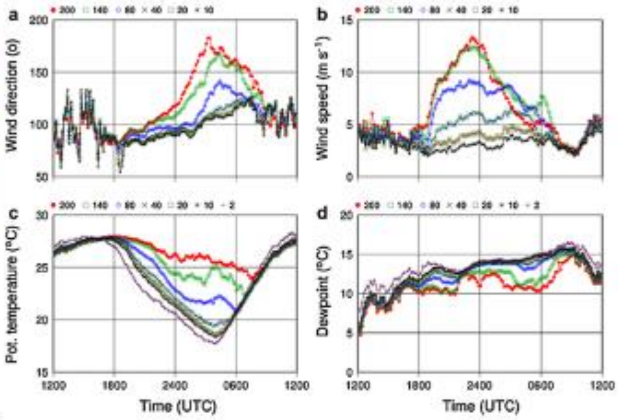
Cabauw (Netherlands)



30 km

- Stationary synoptic
- Clear skies
- No fog
- Substantial LLJ

6 years → 9 days → night of 1–2 July 2006



Bosveld et al. (2014) The third GABLS Intercomparison case for evaluation studies of Boundary-Layer Models Part A: Case Selection and Set-Up. Boundary –Layer Meteorol 152: 133-156

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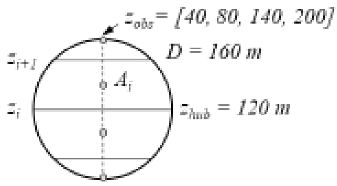
Wind Energy Quantities of Interest

- Hub-height wind speed and direction S_{hub}, WD_{hub}
- Rotor Equivalent Wind Speed *REWS*



$$REWS = \left[\frac{1}{A}\sum_i \left(A_i S_i^3 \cos\beta_i\right)\right]^{1/3}$$

β_i : veer angle with respect to hub-height wind direction

- Wind speed shear, α, and direction veer ψ

$$S_i = S_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha} \qquad \beta_i = WD_i - WD_{hub} = \psi\left(z_i - z_{hub}\right)$$

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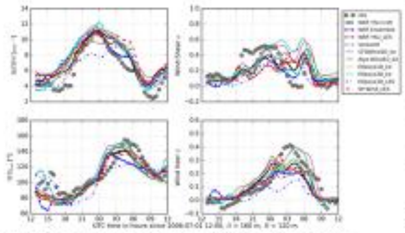
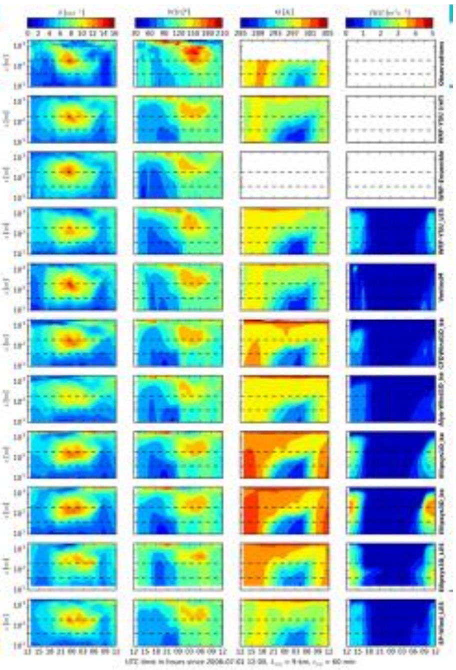
GABLS3 Benchmark

Table 1: Summary of model simulations. Monin-Obukhov similarity theory (MOST) surface boundary conditions use either heat flux (H), 2-m (T_2) or skin temperature (T_{SK}) from WRF

Name	Input	Turbulence	z-Levels	Surface B.C.
WRF-YSU (ref)	ERA Interim	YSU	46	Noah
WRF	ERA Interim, GFS	MYJ, MYNN, QNSE, TEMF, YSU	46	Noah
WRF-YSU_LES	ERA Interim	LES-TKE	101	Noah
WRF-VortexM_ke	ERA Interim	YSU/k-ε	70	MOST, H
CFDWind1D_ke	WRF (ref)	k-ε	301	MOST, T_2
Alya-CFDWind1D_ke	WRF (ref)	k-ε	500	MOST, T_2
Ellipsys1D_ke	WRF (ref)	k-ε	512	MOST, T_{SK}
Ellipsys3D_ke	WRF (ref)	k-ε	192	MOST, T_{SK}
Ellipsys3D_LES	WRF (ref)	Smagorinsky	128	MOST, T_{SK}
SP-Wind_LES	WRF (ref)	LES-TKE	500	MOST, T_2





Sanz Rodrigo J, Churchfield M, Kosović B (2016) A wind energy benchmark for ABL modeling of a diurnal cycle with a nocturnal low-level jet: GABLS3 revisited. Journal of Physics: Conference Series 753, 032024

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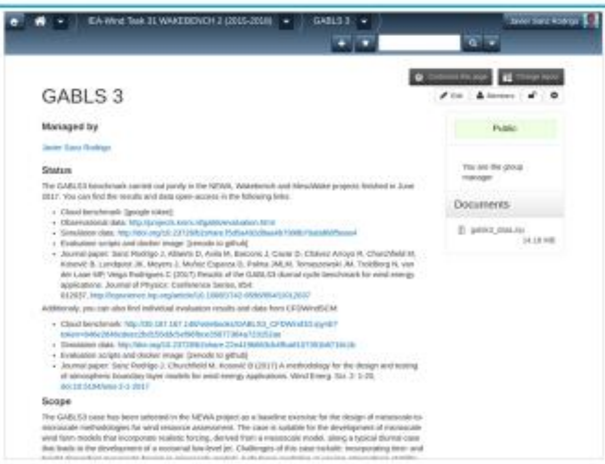
GABLS3: Benchmark Guide



http://windbench.net/gabls-3

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GABLS3: Open Science Approach

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Towards Phase 3 (June'18-June'21): Wish list so far

- High-Fidelity Modeling (LES) and building better design tools
- Integrated model validation (flow + turbine response)
- Unified strategy for V&V: targeted research experiments as well as industry data procurement
- Data mining for model improvement
- More systematic study of wake models
- Wind farm phenomena: yaw misalignment, blockage (acceleration within wind farm gaps), wake dissipation (interaction with background turbulence), heterogeneous inflow (coastal for instance), curtailment, large wind farm boundary layer (interaction with free-atmosphere conditions), wake effects at mesoscale (North Sea), etc.
- Numerical scanning lidar for apples-to-apples validation
- Collaboration with neighboring IEA Tasks, Tasks, notably Task 30 (offshore design codes) and Task 32 (lidar)

CENER

Gobierno de Navarra

Towards Phase 3 (June'18-June'21): Available Data

- Wind and Site: NEWA Experiments, flow cases and AEP
  - ❑ Kassel forested hill
  - ❑ Hornamossen forested hilly-terrain
  - ❑ Perdigao double-hill
  - ❑ Alaiz hill-mountain
  - ❑ Ferry lines (Baltic Sea)
  - ❑ RUNE coastal transition
  - ❑ Balcony heterogeneous canopy
- Turbine Performance
  - ❑ Alpha Ventus (with Task 30)
  - ❑ A2e-SWiFT experiments, wake steering
- Wind Farm Performance
  - Horns Rev, Lillgrund: UQ engineering wake models
  - OWA-Rodsand 2 scanning-lidar experiment, heterogeneous inflow

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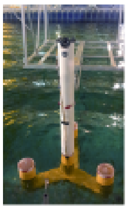
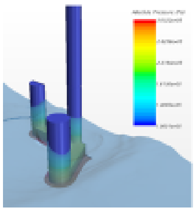
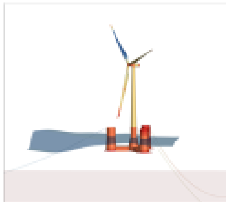
Comparison of Wave Tank Tests, CFD and Engineering Model Computations of Floaters with Mooring Lines

IEA WIND TASK 11 TOPICAL EXPERT MEETING #88
THREE-WAY VERIFICATION AND VALIDATION BETWEEN DATA, HIGH-FIDELITY MODELS, AND ENGINEERING MODELS
Edinburgh, September 6 – 8, 2017



Tor Anders Nygaard tor.anders.nygaard@ife.no
Luca Oggiano, Fabio Pierella, Jacobus de Vaal and Roy Stenbro

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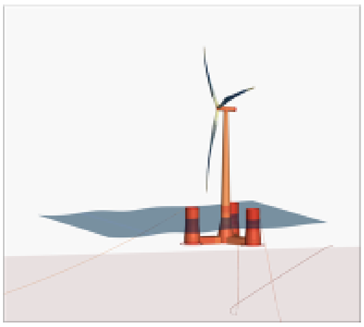
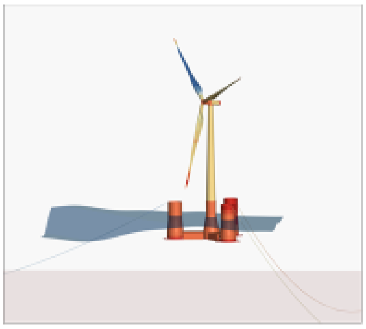
3DFloat Integrated (Engineering) Model

Stability and fatigue at rated power



Survival at ultimate limit state



2

3DFloat

- Finite Element Method (FEM)
- Currently Euler-Bernoulli beams with 12 degrees of freedom (DOF), but framework is general and can later accept other types of elements
- Newmark and Generalized Alpha implicit time integration schemes. Central difference explicit scheme.
- Eigen-frequency analysis
- Geometric nonlinearities accounted for by corotated approach. Reference configuration is recent deformed state.
- Consistent (distributed) loads from gravity, waves, current, buoyancy and wind.
- Point forces can be applied to nodes
- Wind turbine rotors (BEM) (several if so desired) can be associated to nodes
- Mooring lines can be represented directly in the FEM model

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More information, 3DFloat

- Nygaard, T. A., De Vaal, J., Pierella, F., Oggiano, L. and Stenbro, R. (2016). *Development, Verification and Validation of 3DFloat; Aero-Servo-Hydro-Elastic Computations of Offshore Structures.* Energy Procedia (DeepWind 2016).
- This paper is available online and has references to the verification and validation history of 3DFloat
- The verification/validation history involves all offshore windturbines since the OC3-HYWIND in the IEA OC3/4/5 projects and wave tank tests.

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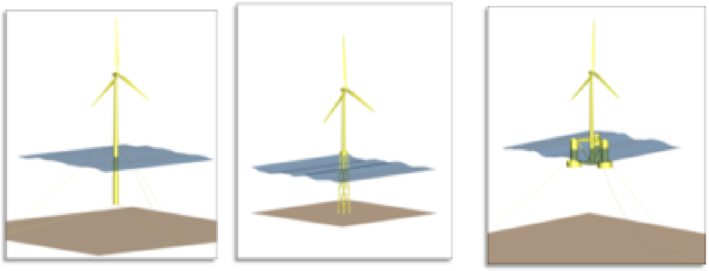
Code to code verification: IEA OC3/OC4/OC5

2010 2012 2014



5

Verification of 3DFloat for floating bridges

- 3DFloat was compared with OrcaFlex (time-domain) and NovaFrame (frequency domain) for the phase 2 version of the Bjørnafjorden K7 End-Anchored Floating Bridge (5km)

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Data available for validation within NOWITECH (NTNU, SINTEF, MARINTEK and IFE)

- Wave tank tests of fixed, rigid and flexible cylinders at MARINTEK and DTU (IEA OC5)
- Wave tank tests of semisubmersible at MARIN (IEA OC5)
- Full-scale data, bottom-fixed wind turbines from Alpha-Ventus (IEA OC5, ongoing)
- Wave tank test of Tension-Leg-Buoy at IFREMER, Brest (IFE/NMBU) MARINET
- Wave tank test (software-in-the loop) of OO Star Semi at ECN, Nantes (CENER/IFE/NMBU) MARINET
- Wave tank test of catenary mooring line with forced motion of fairlead, ECN, Nantes (CENER/IFE/NMBU) MARINET
- Wave tank test (software-in-the loop) of semi-submersible at MARINTEK (NOWITECH)
- Wave-tank test of monopile at MARINTEK (ongoing) (NOWITECH)
- Wind tunnel tests of wind turbine rotors at NTNU (NOWITECH)
- MEXICO and MEXNEXT wind tunnel tests, IEA projects

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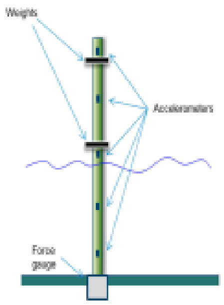
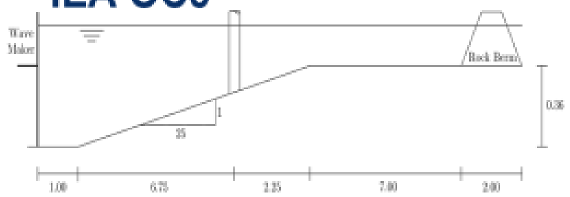
IFE

Fixed, flexible cylinders DHI and DTU. IEA OC5





Robertson, A., Wendt, F., Jonkman, J., Popko, W., Borg, M., Bredmose, H., Schlutter, F., Qvist, J., Bergua, R., Harries,R., Yde, A., Nygaard, T.A., De Vaal, J.B., Oggiano, L., Bozonnet, P., Bouy, L., Sanches, C.B., Garcia, R.G, Bachynski, E., Tu, Y., Bayati, I., Borisade, F., Shin, H., van der Zee, T., Guerinel, M. (2016). *OC5 Project Phase Ib: Validation of Hydrodynamic Loading on a Fixed, Flexible Cylinder for Offshore Wind Applications*. Energy Procedia 2016 ;Volume 94. pg. 82-101

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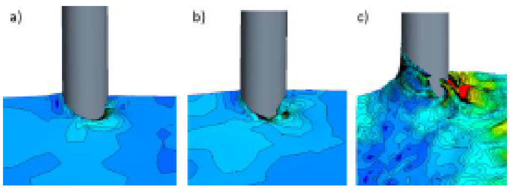
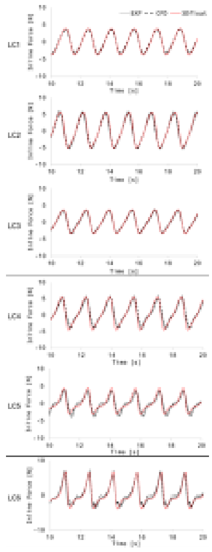
3DFloat: Rainey and 10th order stream function for 'mild' cases, full potential kinematics imported for cases with strong nonlinearities





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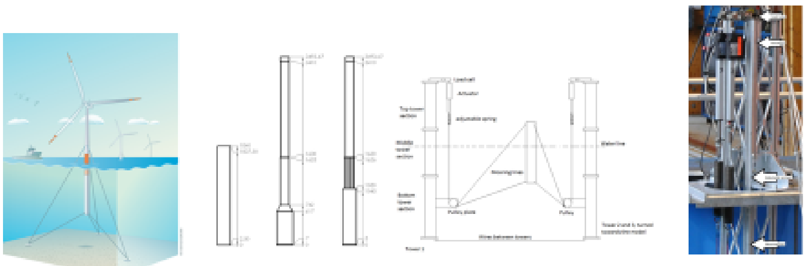
Tension-Leg-Buoy, IFREMER, Brest, 2012



Myhr, A. and Nygaard, T. A. (2014). *Experimental Results for Tension-Leg-Buoy Offshore Wind Turbine Platforms*. Journal of Ocean and Wind Energy, 2014, Vol. 1, No. 4

Myhr, A. and Nygaard, T. A. (2015). *Comparison of Experimental Results and Computations for Tension-Leg-Buoy Offshore Wind Turbines*. Journal of Ocean and Wind Energy, 2015, Vol. 2, No. 1

Oggiano, L., Arens, E., Myhr, A., Nygaard, T.A. and Evans, S. (2015). CFD Simulations on a Tension Leg Buoy Platform for Offshore Wind Turbines and Comparison with Experiments. Proceedings of the 25th (2015) International Offshore and Polar Engineering Conference (ISOPE), Kona, Big Island, Hawaii, June 2015.

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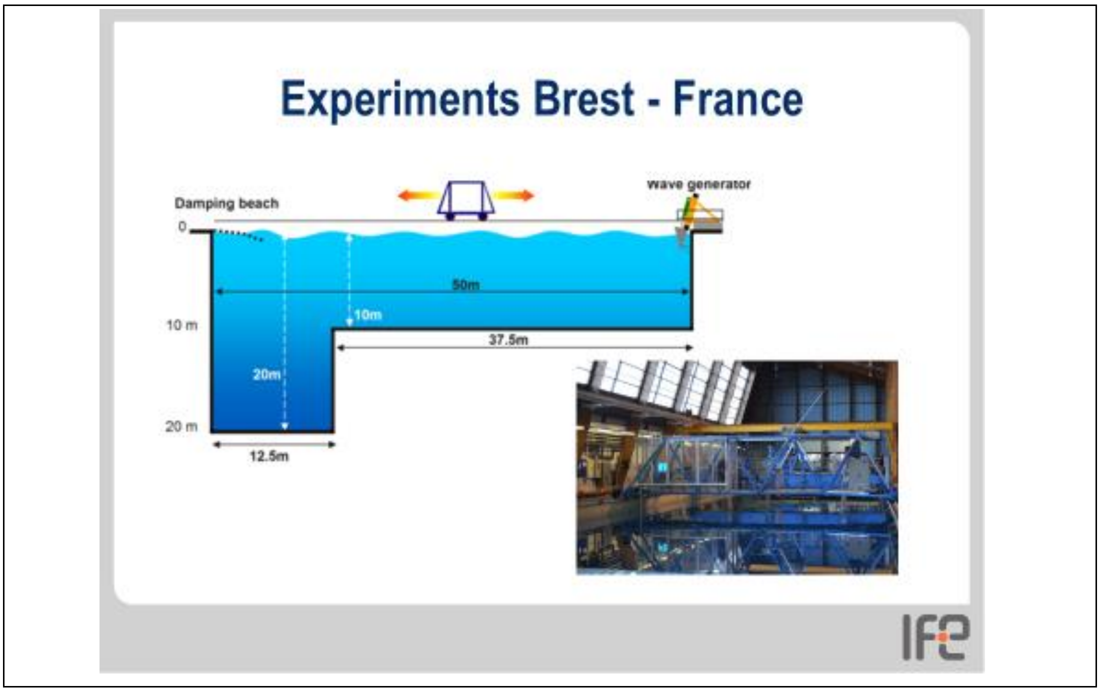
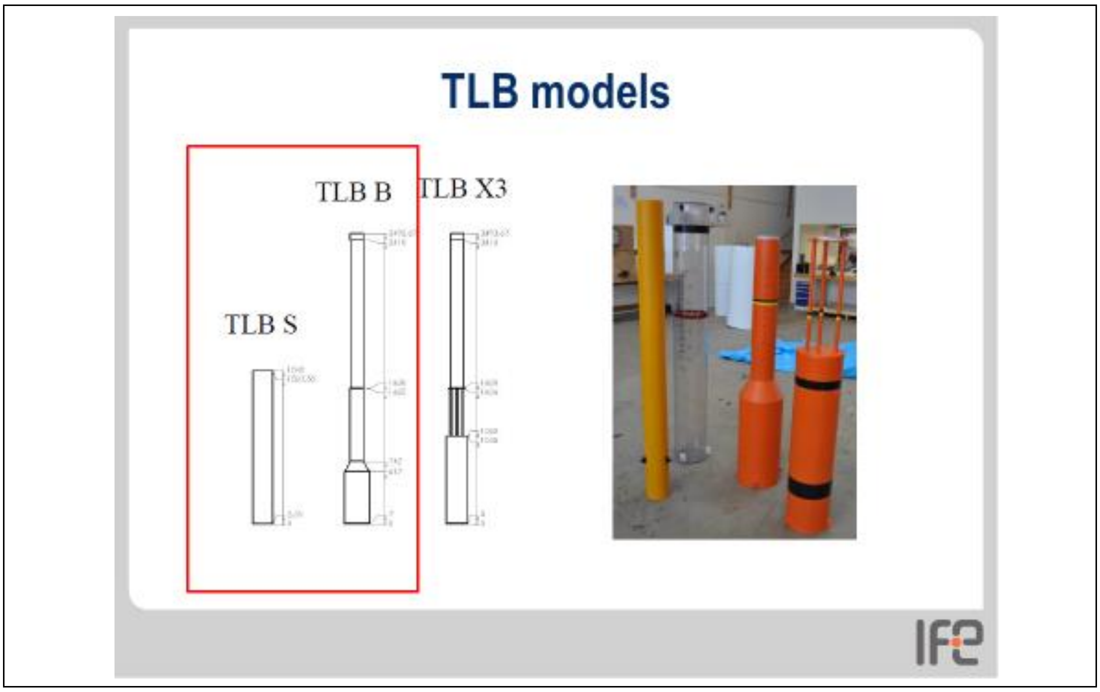
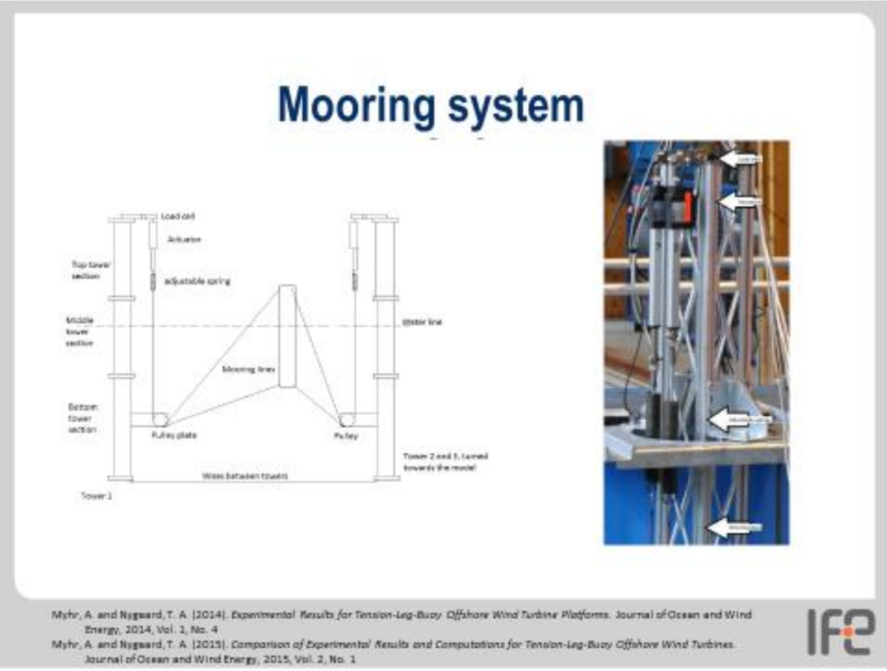
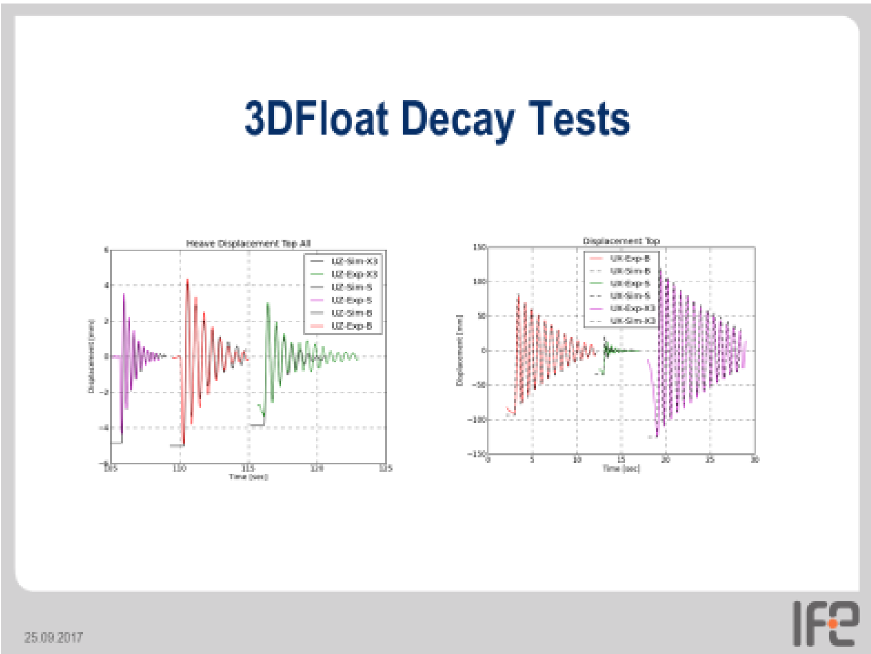
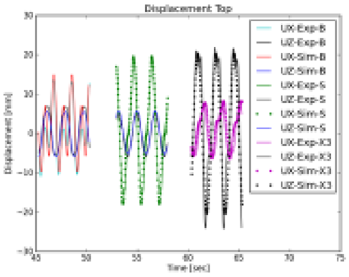

Experiments Brest - France
Damping beach
wave generator
0
10 m
20 m
50m
10m
37.5m
20m
12.5m

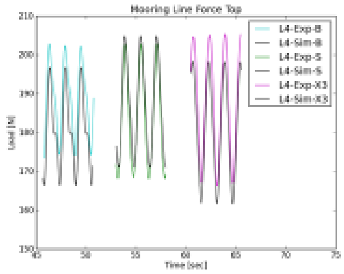

TLB models
TLB B
TLB X3
TLB S


Mooring system
Load cell
Actuator
Top tower section
adjustable spring
Middle tower section
Water line
Mooring lines
Bottom tower section
Pulley plate
Pulley
Tower 2 and 3, turned towards the model
Wires between towers
Tower 1
Myhr, A. and Nygaard, T. A. (2014). *Experimental Results for Tension-Leg-Buoy Offshore Wind Turbine Platforms.* Journal of Ocean and Wind Energy, 2014, Vol. 1, No. 4
Myhr, A. and Nygaard, T. A. (2015). *Comparison of Experimental Results and Computations for Tension-Leg-Buoy Offshore Wind Turbines.* Journal of Ocean and Wind Energy, 2015, Vol. 2, No. 1


3DFloat Decay Tests
Heave Displacement Top All
UZ-Sim-X3
UZ-Exp-X3
UZ-Sim-S
UZ-Exp-S
UZ-Sim-B
UZ-Exp-B
Displacement [mm]
Time [sec]
Displacement Top
UX-Exp-B
UX-Sim-B
UX-Exp-S
UX-Sim-S
UX-Exp-X3
UX-Sim-X3
Displacement [mm]
Time [sec]
25.09.2017

Result examples, regular waves





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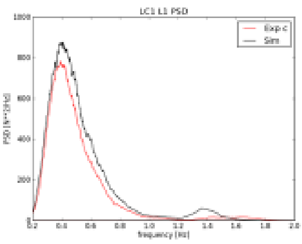
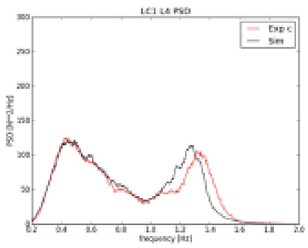
Result examples, irregular waves
Mooring line forces





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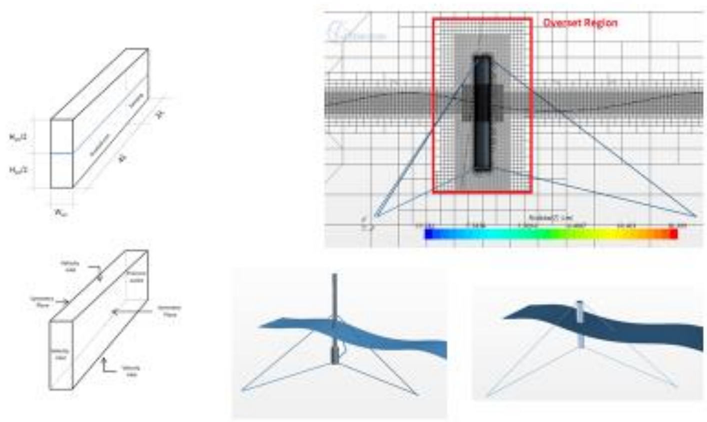
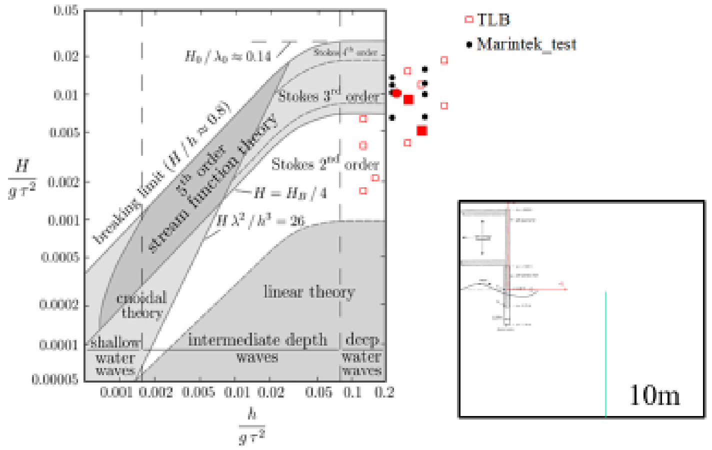
CFD Wave Generation

- STAR-CCM+ provides several wave models:
  - For initialization of volume fraction, velocity and pressure fields;
  - For a transient inlet boundary condition.
- Currently available models:
  - 1 st-order linear wave theory
  - Non-linear 5 th-order Stokes wave theory (Fenton, 1985)
  - Pierson-Moskowitz and JONSWAP long-crested wave spectra
  - Superposition of linear waves with varying amplitude, period and direction of propagation (can be set-up via Excel-file)

TLB - Setup

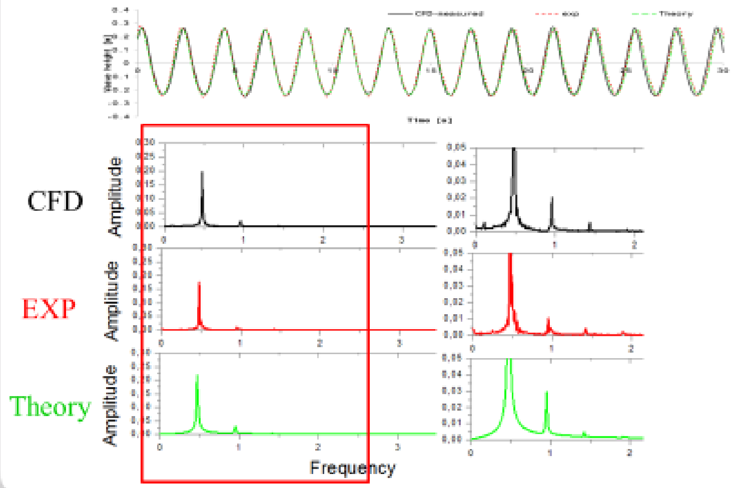




Stansberg, C.T.; Krokstad, J.R.; and Lehn, E., "Experimental Study on Non-Linear Loads on Vertical Cylinders in Steep Random Waves," *Proceedings of the Fifth (1995) International Offshore and Polar Engineering Conference.*
Marthinsen, T.; Stansberg, C.T.; and Krokstad, J.R., "On the Ringing Excitation of Circular Cylinders", *Proceedings of the Sixth (1996) International Offshore and Polar Engineering Conference.*
Stansberg, C.T., "Comparing Ringing Loads from Experiments with Cylinders of Different Diameters – An Empirical Study", *Proceedings, vol. 2, the BOSS '97 Conference, Delft, The Netherlands.*

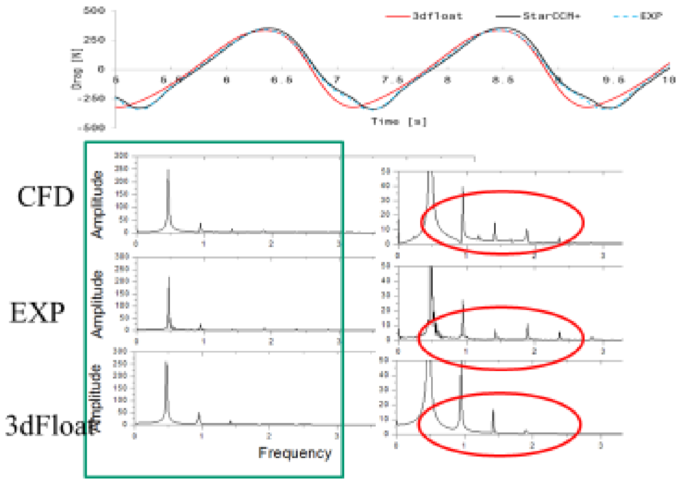
IFE

WAVES LC15 (Marintek) h=10,H=0.52, T=2.1



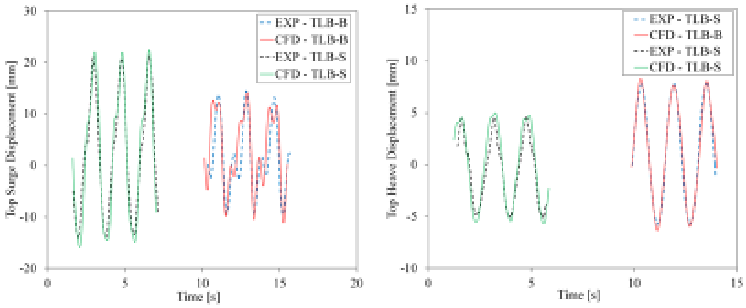
IFE

LOADS LC15 (Marintek) h=10,H=0.52, T=2.1



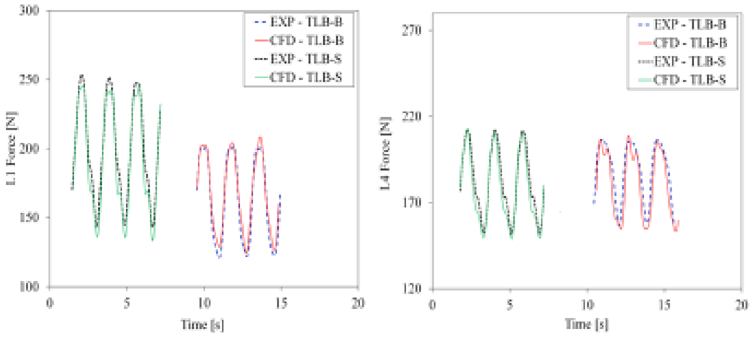
LOAD CASE 12 – Surge Heave

Model T =1.8s H=0.3m
Full Scale T=12 s H 8.2 m

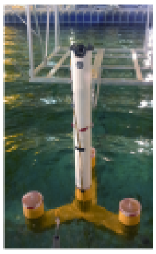


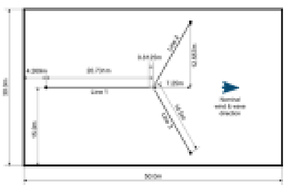
LOAD CASE 12 Mooring lines foces

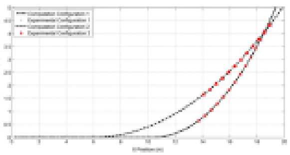
Model T =1.8s H=0.3m
Full Scale T=12 s H 8.2 m



OO Star Semisub, ECN Nantes



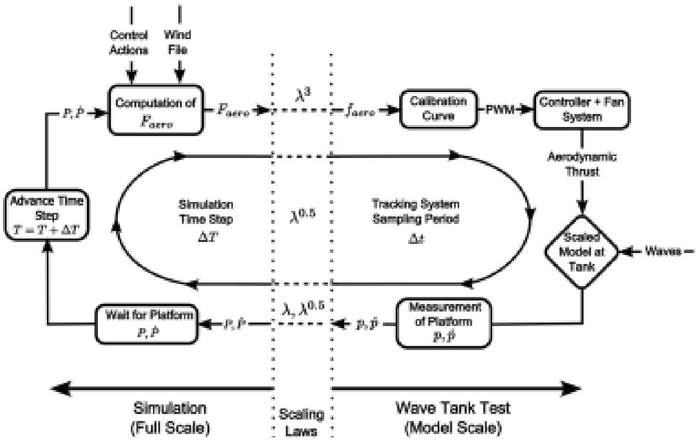




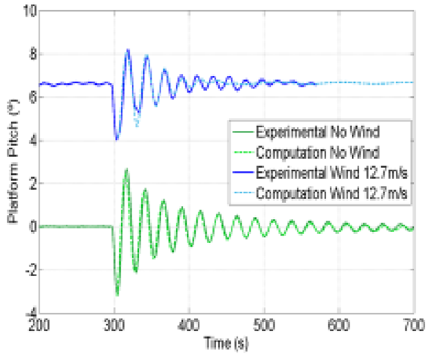
Azcona, J., Bouchotrouch, F., González, M., Garciand, J., Munduate, X., Kelberlau, F. and Nygaard, T.A. (2014). *Aerodynamic Thrust Modelling in Wave Tank Tests of Offshore Floating Wind Turbines Using a Ducted Fan*. Journal of Physics: Conference Series 524 (2014) 012089.

Azcona, J., Munduate, X., González, L., and Nygaard, T.A. (2017). *Experimental Validation of a Dynamic Mooring Lines Code with Tension and Motion Measurements of a Submerged Chain*. Ocean Engineering 2017, Vol. 129, pg. 415-427.

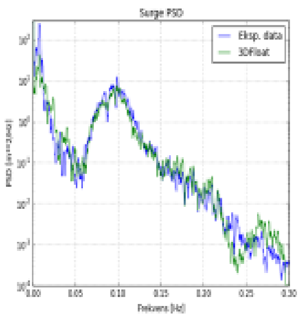
Software-in-the-loop system



FAST/OPASS and 3DFloat results



From Azcona et al., 2014



From Masters's thesis of Engelsvold, NMBU, 2015

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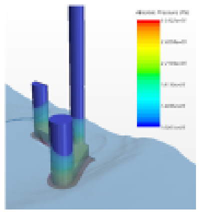
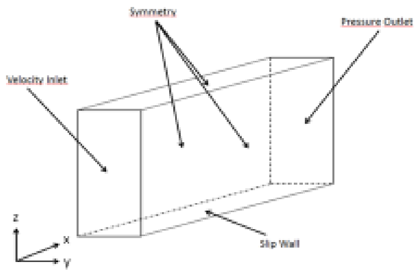
OO Star CFD Computations



Oggiano, L., Pierella, F., Nygaard, T.A., De Vaal, J.B. and Arens, E.(2016) *Comparison of Experiments and CFD Simulations of a Braceless Concrete Semi-submersible Platform*. Energy Procedia 2016, Volume 94. pg. 278-289

General wave tank setup (BC)



Setup Regular waves Fixed

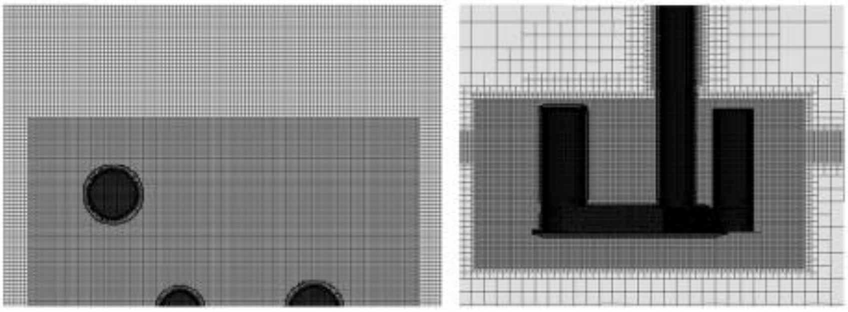
- Half Model
- Fixed mesh
- Model postioned 1L from the inlet
- 5th order Stokes waves
- Ca.500.000 cells
- Refinement in the free surface area

Load cases

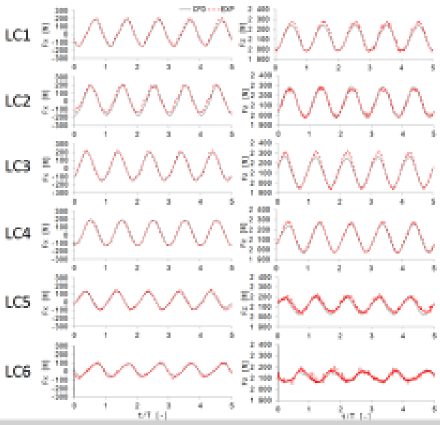
	hull	h m	H m	T s	f Hz
LC 1	fixed	5	0.15	1.26	0.794
LC 2	fixed	5	0.15	1.42	0.704
LC 3	fixed	5	0.15	1.58	0.633
LC 4	fixed	5	0.15	1.74	0.575
LC 5	fixed	5	0.15	2.37	0.422
LC 6	fixed	5	0.15	3.16	0.316

15/12/2015 301

Mesh details



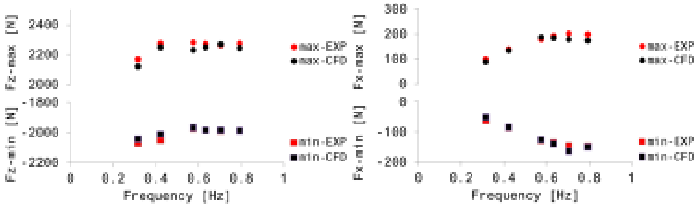
Results



	hull	h	H	T	f
		m	m	s	Hz
LC 1	fixed	5	0.15	1.26	0.794
LC 2	fixed	5	0.15	1.42	0.704
LC 3	fixed	5	0.15	1.58	0.633
LC 4	fixed	5	0.15	1.74	0.575
LC 5	fixed	5	0.15	2.37	0.422
LC 6	fixed	5	0.15	3.16	0.316

Results

Differences between CFD simulations and experiments for maximum and minimum force in the vertical (left) and horizontal (right) direction

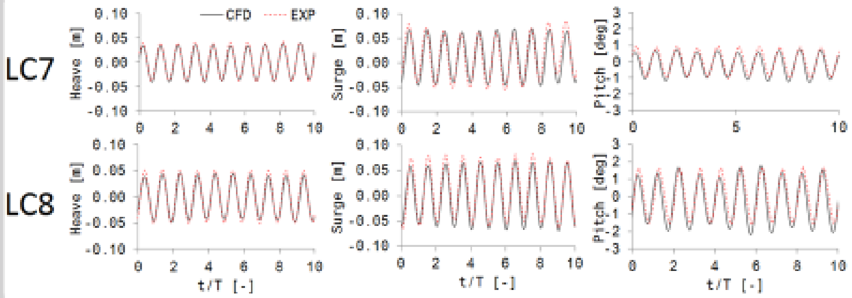


Setup Regular waves free hull

- Full Model
- Overset mesh
- Model postioned 1L from the inlet
- 5th order Stokes waves
- Ca.1500000 cells
- Refinement in the free surface area

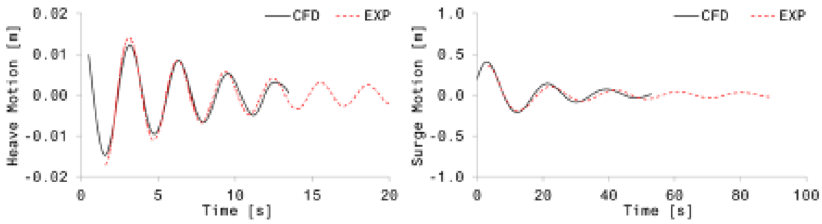
	hull	h m	H m	T s	f Hz
LC 7	free	5	0.16	3.01	0.332
LC 8	free	5	0.16	2.27	0.441

Free hull results

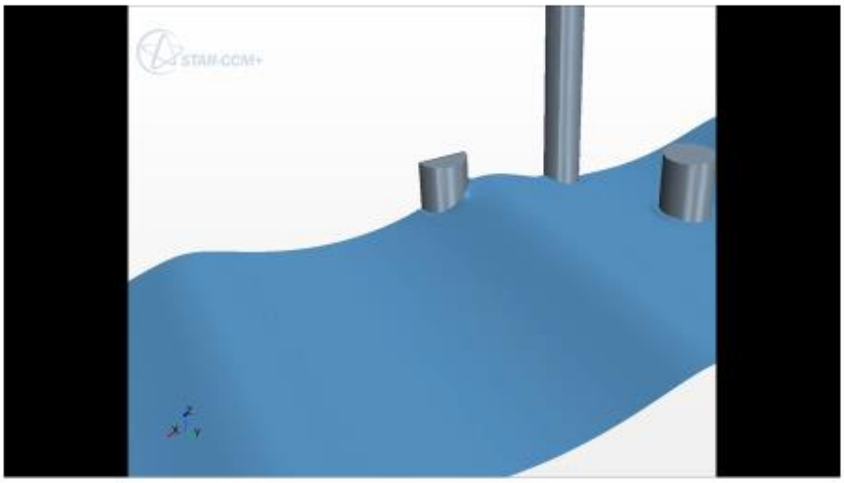


Free hull results

- Decay test



15/12/2015 361



Conclusions

- Simple engineering models such as Morison's equation or Linear Potential Theory, can provide a good match between experiments and computations for the floater types tested so far, if the coefficients are tuned from decay tests in the wave tank.
- The eigen periods can be tuned by adjusting the added mass coefficients. The damping of the first part of the decay can be tuned by adjusting the quadratic drag coefficients. The damping later in the decay can be tuned by adjusting the linear damping coefficients
- CFD has recently demonstrated good results that rely less on tuning for several floater configurations (inertia dominated loads)
- It is encouraging that CFD seems to provide correct damping, which is a problem to determine in the engineering models.

25.09.2017

References, 1

- Azcona, J., Munduate, X., González, L., and Nygaard, T.A. (2017). *Experimental Validation of a Dynamic Mooring Lines Code with Tension and Motion Measurements of a Submerged Chain.* Ocean Engineering 2017, Vol. 129 , pg. 415-427.
- Oggiano, L., Pierella, F., Nygaard, T.A., De Vaal, J.B. and Arens, E.(2016) *Comparison of Experiments and CFD Simulations of a Braceless Concrete Semi-submersible Platform.* Energy Procedia 2016, Volume 94. pg. 278-289
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- Oggiano, L., De Vaal, J., Pierella, F., Arens, E. and Nygaard, T.A. (2016). *Comparison of Experiments and CFD Simulations on a Rigid Monopile in Shallow Water under Regular Waves.* Proceedings of the 26th (2016) International Offshore and Polar Engineering Conference (ISOPE), Rhodes, Greece, June 2016.
- Oggiano, L., Arens, E., Myhr, A., Nygaard, T.A. and Evans, S. (2015). CFD Simulations on a Tension Leg Buoy Platform for Offshore Wind Turbines and Comparison with Experiments. Proceedings of the 25th (2015) International Offshore and Polar Engineering Conference (ISOPE), Kona, Big Island, Hawaii, June 2015.

25.09.2017

References, 2

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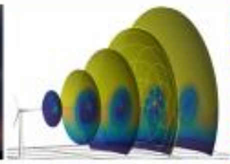
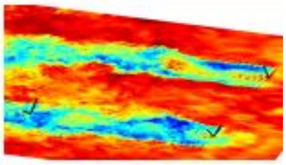



V&V Process in the A2e Initiative

David Maniaci
Wind Energy Technologies Department
Sandia National Laboratories

Jonathan Naughton
Mechanical Engineering Department
University of Wyoming

IEA Wind task 11Topical Expert Meeting #88
Three-Way Verification and Validation
Between Data, High-Fidelity Models, And
Engineering Models
September 6-8, 2017

SAND2017-9336 PE

V&V Definition

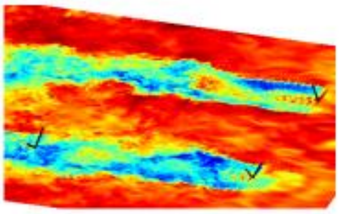
ASME definitions:

- Verification: The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.
- Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

Why invest in V&V?

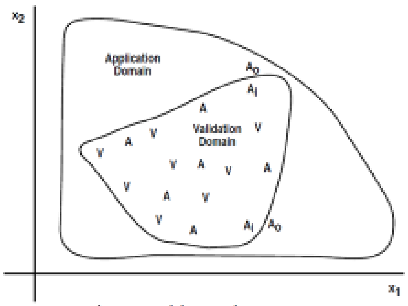
> Increasing Role of Computational Modeling

- As wind turbine technology matures, the cost of testing and the required level of uncertainty demand a new approach
- High fidelity models enable reduced development risk through pre-prototype qualification and optimization
- The Verification and Validation Framework is the process to define the conditions where model predictions can be trusted



V&V Overview

- Verification and validation are integral parts of establishing a model's predictive capability for an intended application.
- Validation is not a pass/fail exercise for a simulation.
  - Assesses the uncertainty of the predictive capability that the user can utilize to judge its suitability for a given application.



x_1 and x_2 are model parameters

What is a Validation Focused Program?

Goal

- Formalized highly collaborative approach to planning and executing joint experimental/modeling programs for the purpose of characterizing model accuracy for an intended application

Why?

- Provides a transparent, structured, documented approach for integrate program planning across scales
- Applicable to models of all fidelity, including reduced order models
- High quality data sets well suited for collaborative model validation efforts
- Quantifies prediction uncertainty for use by designers

Foundation of framework used

- Framework developed for nuclear energy, SNL NW, and other programs
- Framework consistent with various ASME and AIAA V&V Guides, Codes and Standards

V&V Framework

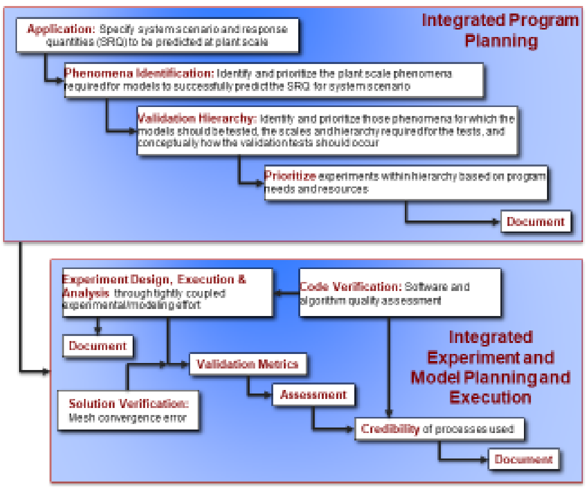
(2015 Hills, Maniaci, Naughton)

Integrated Planning

- Program leaders, modelers, software developers, experimentalists, V&V specialists

Validation Planning

- Domain specific program leaders, modelers, experimentalists, V&V specialists, data acquisition specialists



Primary Stakeholders

- **DOE Wind Energy Technologies Office**: improve understanding of wind plant complex flow, exploration of novel wind technology advances and validation of lower-fidelity models
- **Manufacturers**: improved energy capture and reliability of wind turbines through technology development and environment definition
- **Developers**: design optimized wind plants, quantify and reduce uncertainties in energy estimates
- **Owners/Operators**: maximize energy capture and reliability of existing farms, improved day-ahead and hourly forecasting

Application Use Cases

- **Predict**
  - Wind plant power performance and loads
  - Power production of a wind plant in at terrain, with blade-root loads
  - Diurnal flow field in complex terrain (pre-wind plant installation)
  - Loads and wakes of a next-generation turbine (qualification)
  - Forensics analyses with data assimilation to understand extreme or unusual load events
- **Discover**
  - Dominant phenomena governing wake evolution
  - New modeling approaches for wind energy
- **Innovate**
  - Explore the design space of next generation innovations to improve turbine and plant performance
  - Optimize new technology prior to demonstration testing

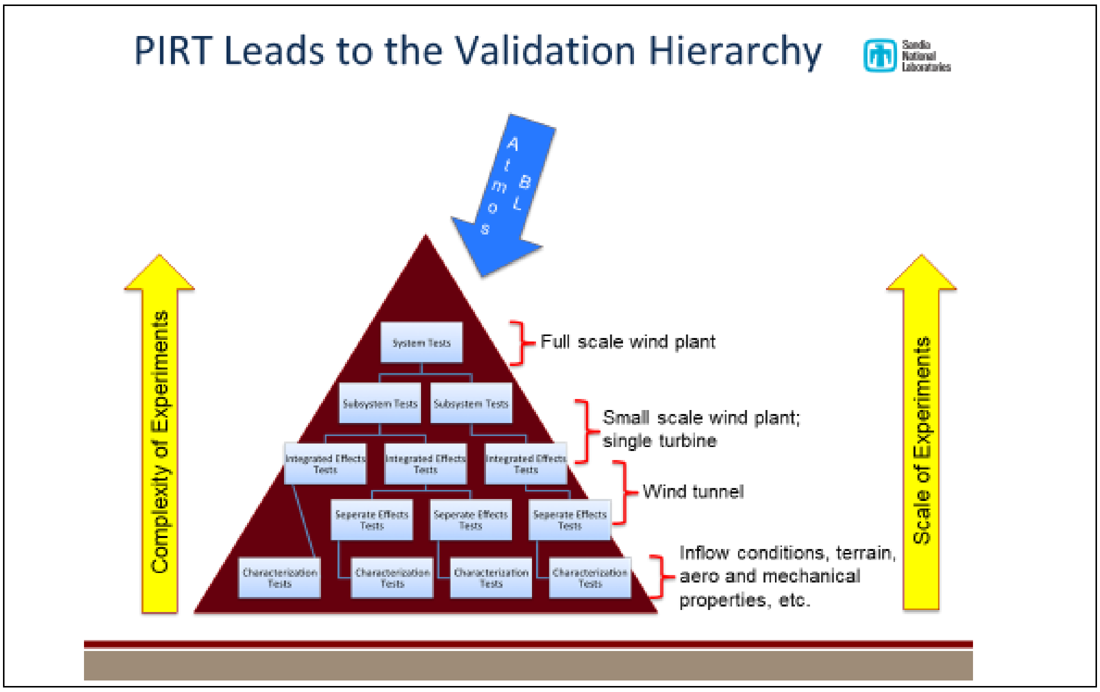
V&V Hierarchy

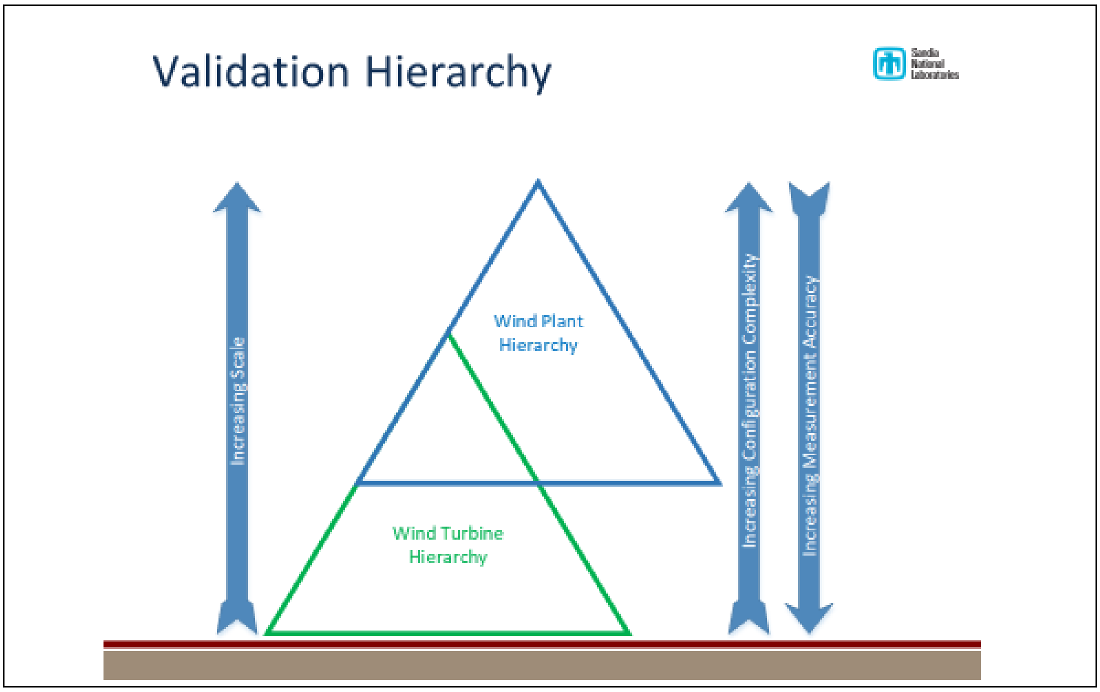
Backbone of Prioritization Process: PIRT

PIRT: Phenomenon Identification Ranking Table

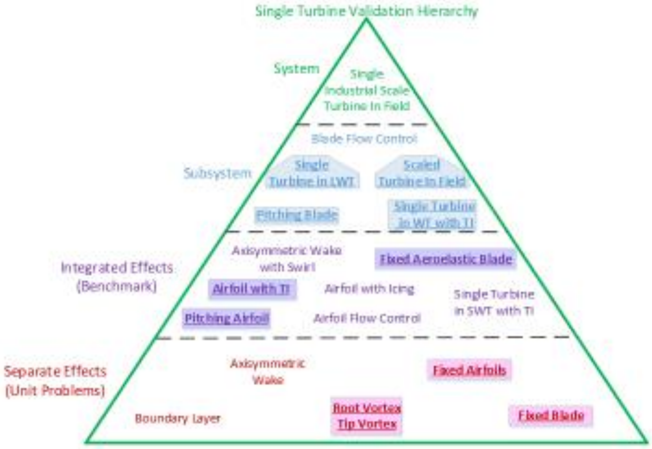
- Consensus based
- Provides gap analysis of ability to model phenomena
  - Physics gaps
  - Numerical gaps
  - Data gaps
  - Validation gaps
- Gap analysis used to prioritize planning, including experimental planning

Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Turbine scale flow phenomena				
Blade Aero / Wake Generation				
Blade load distribution effects and rotor thrust	H	M	L	L
Tip and root vortex development, and evolution and merging	H	M	L	L
Vortex sheet and rollup (in addition to tip/root vortex)	M	M	M	L
Blade generated turbulence characteristics (energetic scales)	H	L	L	L
Root flow acceleration effect ("hub jet")	Unknown	M	L	L
Boundary layer state on turbine performance (roughness, soiling, bugs, erosion)	H	L	L	L
Boundary layer state (Re)	L	M	L	L
BL details near TE and LE	H	M	L	L
Rotational augmentation	H	L	L	L
Dynamic stall	H	L	L	L
Unsteady inflow effect (turb. intensity, spectra, coherence, veer, shear)	H	L	L	L
Blade flow control	M	L	L	L
Tower/rotor/nacelle wake interactions	H	M	L	L
Icing	L	L	L	L

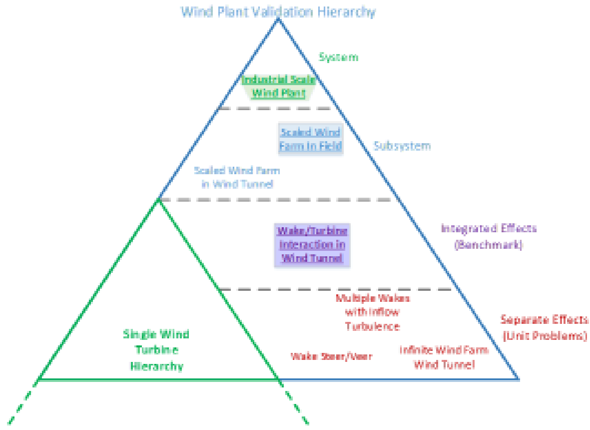

PIRT Leads to the Validation Hierarchy
Sandia National Laboratories
Atmos
ABL
Complexity of Experiments
Scale of Experiments
System Tests
Subsystem Tests
Subsystem Tests
Integrated Effects Tests
Integrated Effects Tests
Integrated Effects Tests
Seperate Effects Tests
Seperate Effects Tests
Seperate Effects Tests
Characterization Tests
Characterization Tests
Characterization Tests
Characterization Tests
Full scale wind plant
Small scale wind plant; single turbine
Wind tunnel
Inflow conditions, terrain, aero and mechanical properties, etc.


Validation Hierarchy
Sandia National Laboratories
Increasing Scale
Wind Plant Hierarchy
Wind Turbine Hierarchy
Increasing Configuration Complexity
Increasing Measurement Accuracy

Wind Turbine Validation Hierarchy



Wind Plant Validation Hierarchy



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Phenomena Mapping to Experiments

PPEM (Prioritized Phenomenon Experiment Mapping)

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Wind Plant

Physics Present/Physics Measured

- Entirely
- Mostly
- Somewhat
- Limited
- Missing

	Multi-Turbine Wake Effects	Interaction, Merging, Motion	Steering (Yaw/Tilt Effects)	Wake Dissipation	Wake Impingement (Full/Half/Near)	Inflow Turbulence Wake Interaction	Wind Direction	Surface Conditions	Turbulence Statistics	Momentum Transport
Industrial Scale Wind Farm in (60 m rotor)										
Physics Present		Entirely	Entirely	Entirely	Entirely		Entirely	Entirely	Entirely	Entirely
Physics Capture by Measurements		Limited	Limited	Limited	Limited		Somewhat	Mostly	Limited	Limited
Scaled Wind Farm in Field (20 m rotor)										
Physics Present		Entirely	Entirely	Mostly	Entirely		Entirely	Mostly	Mostly	Mostly
Physics Capture by Measurements		Somewhat	Somewhat	Limited	Somewhat		Mostly	Mostly	Somewhat	Limited
Scaled Wind Farm in VL WT (2 m rotor)										
Physics Present		Mostly	Mostly	Somewhat	Mostly		Entirely	Somewhat	Somewhat	Somewhat
Physics Capture by Measurements		Mostly	Mostly	Mostly	Entirely		Entirely	Entirely	Mostly	Mostly
Wake/Turbine Interaction in WT (2 m rotor)										
Physics Present		Limited	Mostly	Limited	Mostly		Somewhat	Somewhat	Mostly	Mostly
Physics Capture by Measurements		Mostly	Mostly	Somewhat	Entirely		Entirely	Entirely	Mostly	Mostly

D. Maniaci and J. Naughton, 2017

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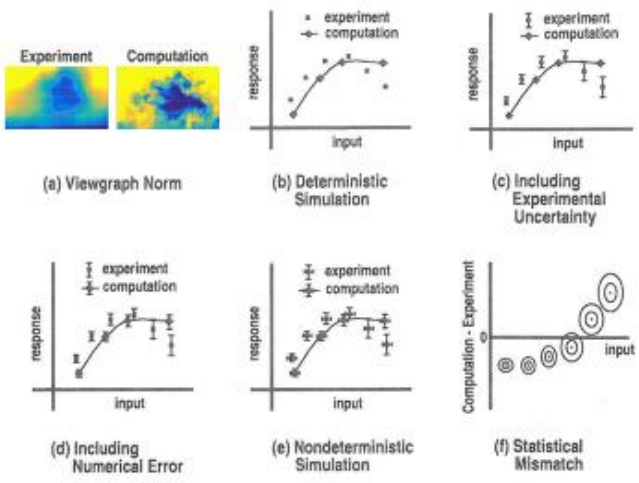
Uncertainty Quantification

Uncertainty Quantification

Levels of Precision



(a) Viewgraph Norm

(b) Deterministic Simulation

(c) Including Experimental Uncertainty

(d) Including Numerical Error

(e) Nondeterministic Simulation

(f) Statistical Mismatch

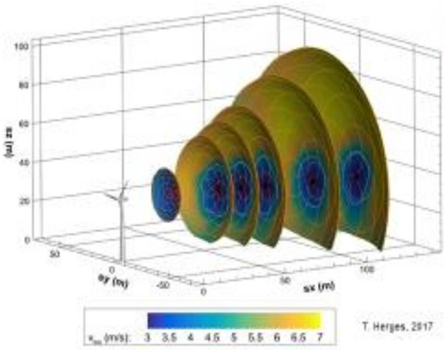
Modified from Oberkamf and Roy, 2012

Example Validation Dataset

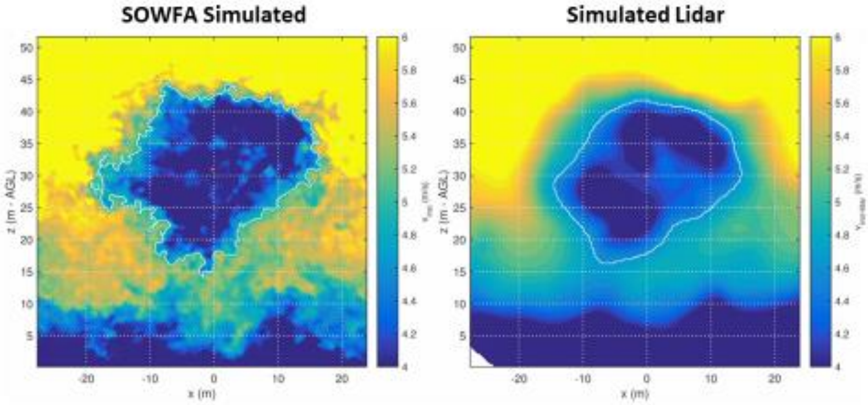
SWiFT Wake Measurements

DOE/SNL Scaled Wind Farm Technology (SWiFT) facility hosted by Texas Tech University (TTU)

Objective: Assess the ability of models to predict ***wake shape, strength, and deflection***.



Lidar Simulation and Selection

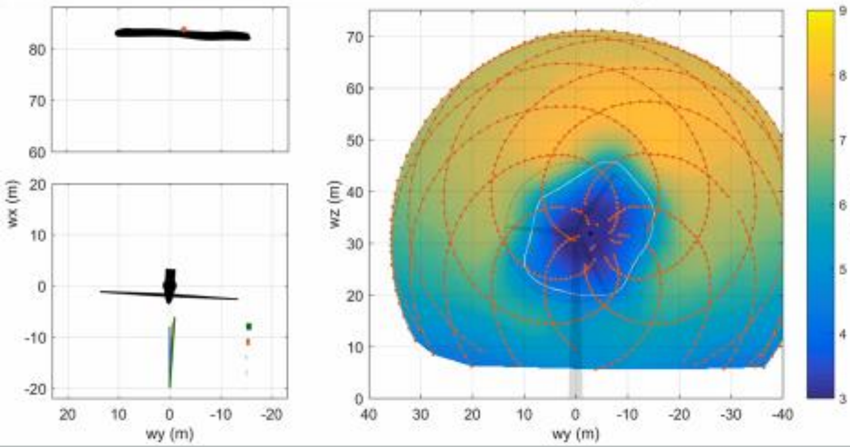


- Comparison of identical time steps in order to show effect of SpinnerLidar on measurements and how that impacts wake position determination
- Measurements at 3D downstream of turbine

- Simulations conducted by Matt Churchfield using SOWFA 131

Measuring impact of turbine state

- Bulk Richardson = 0.7
- z/L = 3.1
- α = 0.3
- wind speed = 7.5 m/s
- TI = 0.08
- veer = 4.4°
- yaw offset = -7.5° to 15°
- Yaw heading = 159.5 degN



T. Herges, 2017 132

V&V Multi-year Goals

- Enable simulation and design of optimized wind plants
- Execute a simulation and modeling campaign to:
  1. Improve the research community's physical understanding of wake dynamics and turbine interaction
  2. Quantify model prediction uncertainty of wake flow dynamics and turbine interaction
- Engage with the public to disseminate results and progress

Summary

Integrated Program Planning complete

- Application identified
- PIRT completed
  - **SMEs involved**
  - **Consensus identified**
- Validation Hierarchy developed
- Validation experiments mapped onto prioritized phenomena (PPEM)
- Report to appear soon
  - **Maniaci and Naughton**

Integrated Experiment and Model Planning and Execution

- Underway for some prioritized validation experiments
  - **Experiments proposed for all levels of validation hierarchy**
  - *Nalu Validation Roadmap*
- Other groups may use this document as well and identify other gaps in scenarios available for validation

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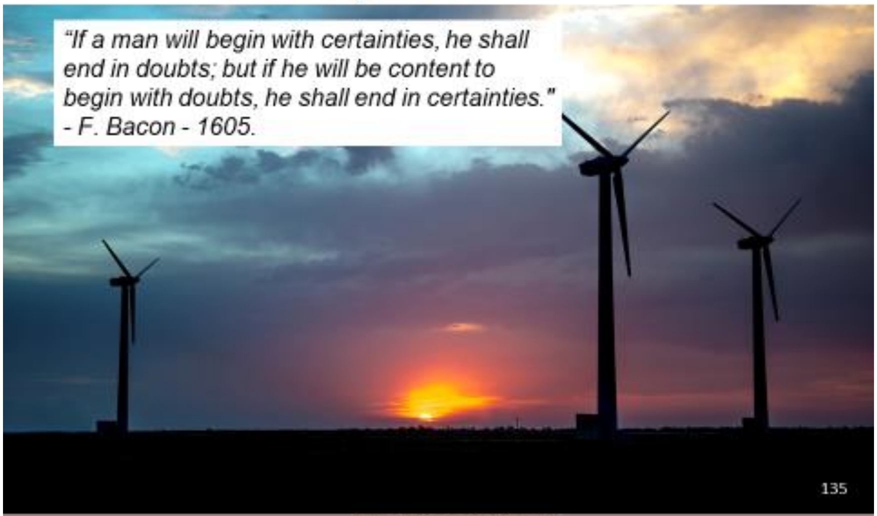
Thank you



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Acknowledgements

- Contributions by Jonathan Naughton (University of Wyoming) and Rich Hills on the application of the V&V process to wind energy are acknowledged
- Input from experts in wind energy and related areas are too many to list, but are acknowledged
- Particular thanks to Pat Moriarty, Brian Naughton, Tommy Herges, Scott Schreck, Brian Resor, Mike Robinson, Paul Veers, Fotis Sotiropoulos, Daniel Laird, Brian Resor, Matt Barone, Steve Hammond, and David Womble.

Overarching Questions

- What is the balance between studies focused on validation for model predictions and studies focused on scientific discovery and understanding?
- How can we use estimates of aleatory and epistemic uncertainty from measurements to drive simulations for inference/validation?
- How can we use simulations to estimate aleatory and epistemic uncertainty in measurements?
- How can VV&UQ based on lower levels of the V&V Hierarchy be used to estimate uncertainty of full system model predictions?

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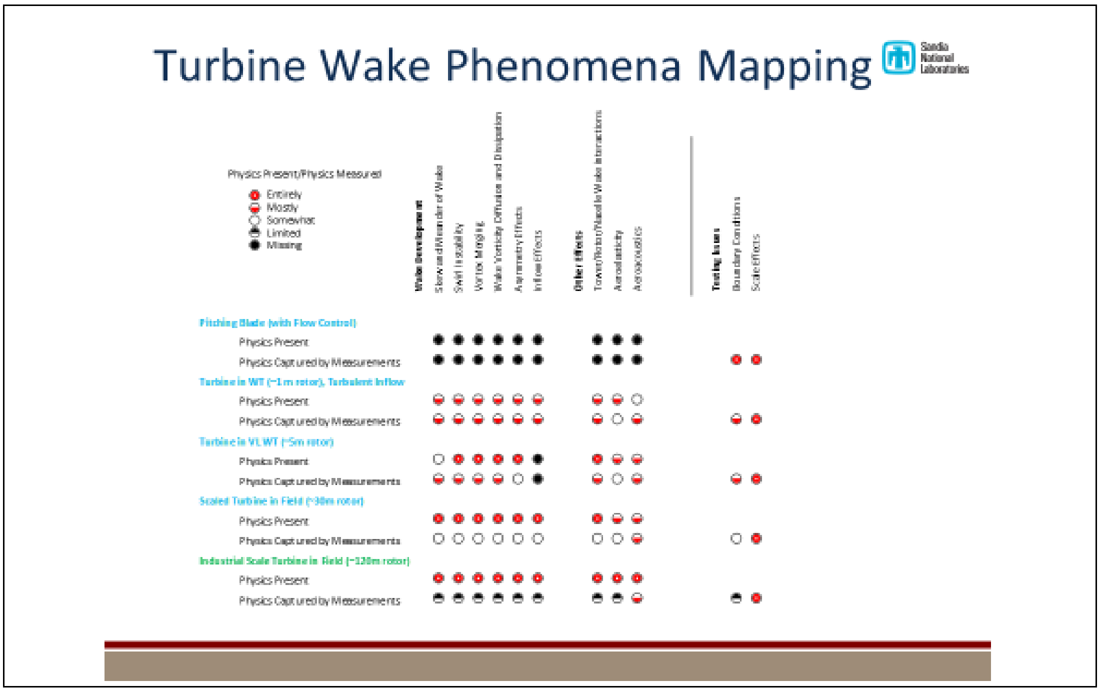
Wind Turbine PIRT

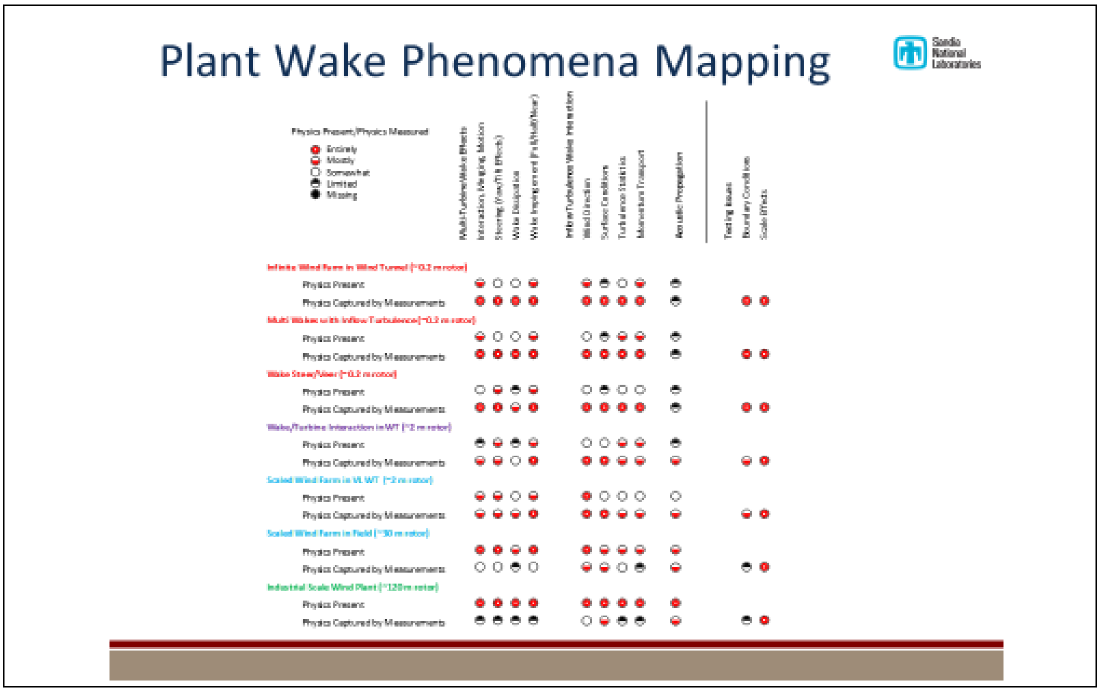
Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Blade Aero / Wake Generation				
Blade load distribution effects and rotor thrust	H	M	L	L
Tip and root vortex development, evolution and merging	H	M	L	L
Vortex sheet and rollup (in addition to tip/root vortex)	M	M	M	L
Blade generated turbulence characteristics (energetic scales at trailing edge)	H	L	L	L
Root flow acceleration effect (hub jet)	Unknown	M	L	L
Boundary layer development (transition, separation)	H	M	L	L
Surface roughness effects (roughness, soiling, bugs, erosion)	H	L	L	L
Boundary layer details near leading and trailing edge	H	M	L	L
Rotational augmentation	H	L	L	L
Dynamic stall	H	L	L	L
Unsteady inflow effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence)	H	L	L	L
Blade flow control	M	L	L	L
Icing	H	L	L	L
Wake Development (growth/recovery)				
Skew and meander of aggregate wake	H	L	L	L
Swirl instability	L	L	L	L
Vortex merging	L	L	L	L
Wake vorticity diffusion and dissipation	H	L	L	L
Asymmetry effects (ground plane, yaw, tilt, cone-angle)	M	M	L	L
Inflow effect (shear, veer, yaw, turb. intensity, turb. spectrum, coherence, gusts, atmos. stab.)	H	L	L	L

Wind Plant PIRT

Phenomenon	Importance at Application Level	Model Adequacy: Physics	Model Adequacy: Code	Model Adequacy: Val
Inflow Turbulence/Wake Interaction				
Wind direction (shear/veer/assymetry)	H	L	M	M
Turbulence characteristics (intensity, spectra, coherence, stability)	H	L	M	M
Coherent turblence structure	H	L	M	L
Surface conditons (roughness, canopy, waves, surface heat flux, topography)	H	L	M	M
Momentum transport (horizontal and vertical fluxes)	H	L	L	L
Multi-Turbine Wake Effects				
Wake interaction, merging, meander	H	L	L	L
Plant flow control for optimum performance	H	M	M	L
Wake steering (yaw & tilt effects)	H	L	L	L
Wake dissipation	H	L	L	L
Wake Impingement (full, half, etc.)	H	L	L	L
Deep array effects (change in turbulence, etc.)	H	L	L	L
Other Effects				
Wind plant blockage effects and plant wake	M	M	M	L
Acoustic Propagation	H	L	L	L

Blade/Aero Phenomena Mapping


Turbine Wake Phenomena Mapping
Sandia National Laboratories
Physics Present/Physics Measured
Entirely
Mostly
Somewhat
Limited
Missing
Wake Development
Skew and Meander of Wake
Swirl Instability
Vortex Merging
Wake Vorticity Diffusion and Dissipation
Asymmetry Effects
Inflow Effects
Other Effects
Tower/Rotor/Nacelle Wake Interactions
Aeroelasticity
Aeroacoustics
Testing Issues
Boundary Conditions
Scale Effects
Pitching Blade (with Flow Control)
Physics Present
Physics Captured by Measurements
Turbine in WT (~1 m rotor), Turbulent Inflow
Physics Present
Physics Captured by Measurements
Turbine in VLWT (~5m rotor)
Physics Present
Physics Captured by Measurements
Scaled Turbine in Field (~30m rotor)
Physics Present
Physics Captured by Measurements
Industrial Scale Turbine in Field (~120m rotor)
Physics Present
Physics Captured by Measurements


Plant Wake Phenomena Mapping
Sandia National Laboratories
Physics Present/Physics Measured
Entirely
Mostly
Somewhat
Limited
Missing
Multi-Turbine/Wake Effects
Interaction, Merging, Motion
Steering (Yaw/Tilt Effects)
Wake Dissipation
Wake Impingement (Full/Half/Near)
Inflow Turbulence Wake Interaction
Wind Direction
Surface Conditions
Turbulence Statistics
Momentum Transport
Acoustic Propagation
Testing Issues
Boundary Conditions
Scale Effects
Infinite Wind Farm in Wind Tunnel (~0.2 m rotor)
Physics Present
Physics Captured by Measurements
Multi Wakes with Inflow Turbulence (~0.2 m rotor)
Physics Present
Physics Captured by Measurements
Wake Steer/Veer (~0.2 m rotor)
Physics Present
Physics Captured by Measurements
Wake/Turbine Interaction in WT (~2 m rotor)
Physics Present
Physics Captured by Measurements
Scaled Wind Farm in VLWT (~2 m rotor)
Physics Present
Physics Captured by Measurements
Scaled Wind Farm in Field (~30 m rotor)
Physics Present
Physics Captured by Measurements
Industrial Scale Wind Plant (~120m rotor)
Physics Present
Physics Captured by Measurements

V&V: Near Term Goals

- Assessed Nalu simulation capability for time-averaged wake offset and strength
  - Move from low uncertainty inflow cases to a matrix of inflow cases
- UQ processes applied for experimental data and model assessment purposes
- Established, demonstrated validation process
- Documentation of model assessment
  - Collaboration through IEA Task 31, Wakebench
- Implement verification processes and tools for HFM

V&V: Communication and Documentation

1. **V&V Framework** (September 2015): the development and execution of coordinated modeling and experiential programs to assess the predictive capability of computational models of complex systems through focused, well structured, and formal processes.
2. **A2e High Fidelity Modeling: Strategic Planning Meetings** (November 2015) : A report on the foundational planning for the A2e High Fidelity Modeling effort for predictive modeling of whole wind plant physics.
3. **V&V Integrated Program Planning for Wind Plant Performance** (July 2016): This document outlines the integrated program planning (IPP) process and applies it to wind plant performance prediction.
4. **Test Objectives and Prioritization for Wind Plant Performance** (July 2016): An intermediary step between the comprehensive information in the IPP document and the detailed planning needed in the integrated experiment and model planning and execution (IEMPE) stages.
5. **Integration into IEA Task 31, Wakebench.** Working toward a collaborative validation process.

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Calibration & Validation of FAST.Farm Against SOWFA

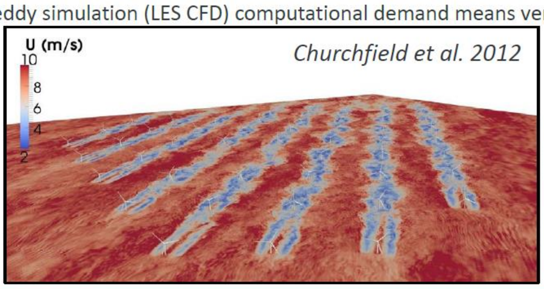
Jason Jonkman, Ph.D.

IEA Wind Task 11 TEM #88
September 6-8, 2017
Edinburgh, UK

The Challenge

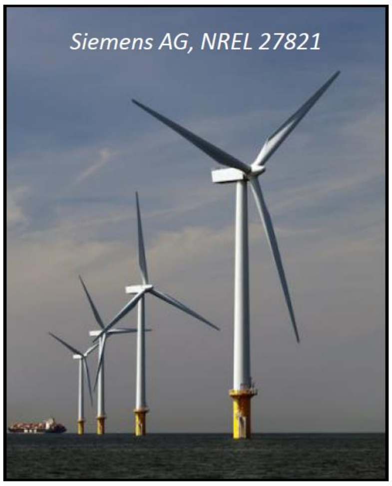
- Wind industry plagued by underperformance, failures, & expenses:
  - Improvements required in wind-farm performance & reliability, together w/ reduced uncertainty & expenditures to achieve cost targets
  - Improvements eluded by complicated nature of wind-farm design, especially interaction between atmospheric phenomena & wake/array effects
- Range of wind-farm tools exist, but none fully meet engineering needs, e.g.:
  - **FLORIS**: Steady-state wind-farm performance & controls, but no turbine loads
  - **DWM**: Both performance & loads, including dynamics, but individual or serial solution limits accuracy & usefulness
  - **SOWFA**: Large-eddy simulation (LES CFD) computational demand means very few runs

Example ***SOWFA*** *Simulation*

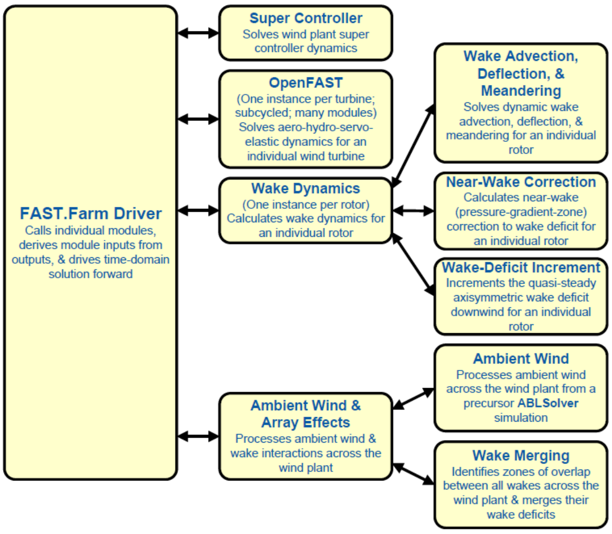


Objective & Approach

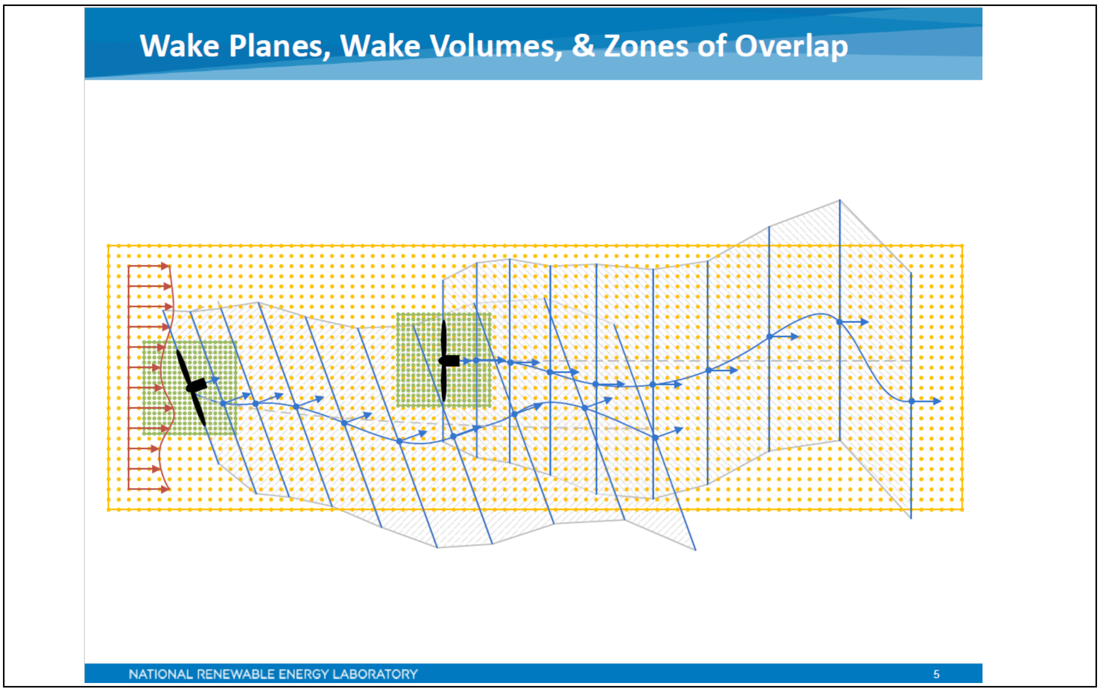
- *Objective*: Develop, validate, & demonstrate new multiphysics tool (**FAST.Farm**) applicable to engineering problems involving wind-farm design
- **FAST.Farm** aims to balance need for:
  - Accurate modeling of relevant physics for predicting performance & loads
  - Maintain low computational cost to support highly iterative & probabilistic design process & system-wide optimization
- **FAST.Farm**:
  - Relies on some **DWM** modeling principles
  - Avoids many limitations of existing **DWM** implementations
  - Compliments controls capability of **FLORIS**
  - Functions more like **SOWFA/Nalu**
- Insight from well-validated **SOWFA** simulations being used to support development, parameter calibration, & validation of **FAST.Farm**

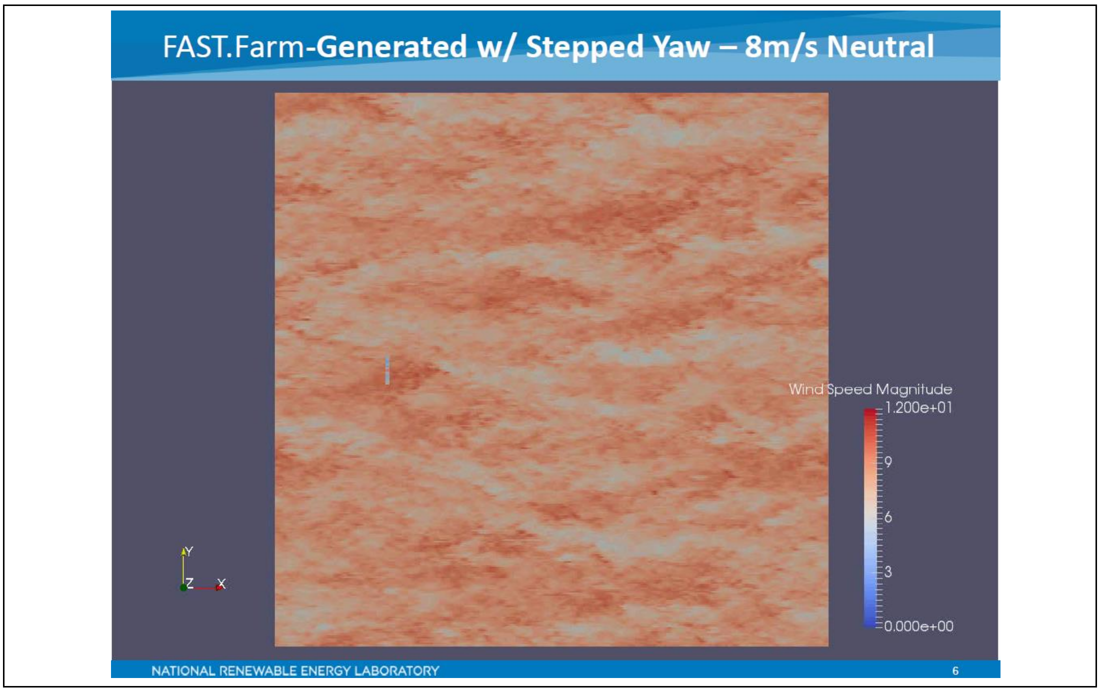


FAST.Farm **Submodel Hierarchy**



- **FAST.Farm** functions nonlinearly in time-domain
- **FAST.Farm** follows requirements of **OpenFAST** modularization framework
- Unique innovations:
  - Use LES precursor for ambient wind
  - Developed new models for wake advection, deflection, & merging
  - Inclusion of a super controller
  - Solve entire wind farm in parallel
  - Calibration of model parameters against HFM


Wake Planes, Wake Volumes, & Zones of Overlap
NATIONAL RENEWABLE ENERGY LABORATORY
5


FAST.Farm-Generated w/ Stepped Yaw – 8m/s Neutral
Wind Speed Magnitude
1.200e+01
9
6
3
0.000e+00
Y
Z
X
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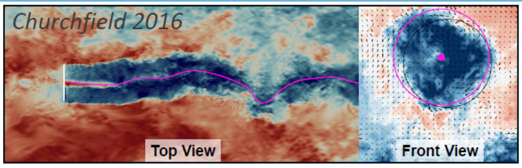
6

Calibration of FAST.Farm Against SOWFA

- **FAST.Farm** contains many (20) parameters that can be used to influence wake dynamics
- A calibration approach is used to set default parameter values
- Approach:
  - Identify calibration cases & approach
  - Identify starting values of calibration parameters
  - Run **SOWFA** & extract wake characteristics
  - Run **FAST.Farm** w/ varied parameters (sequenced grid search & parameter sweep)
  - Identify parameters that minimize wake-deficit & wake-meandering error between **FAST.Farm** & **SOWFA**



***SOWFA**-Derived Wake Deficit & Centerline*

Calibration Cases

Case	Name	Description
1	N	8 m/s, neutral, 10% TI, 0.2 shear, normal operation
2	U	8 m/s, unstable, 10% TI, 0.1 shear, normal operation
3	S	8 m/s, stable, 5% TI, 0.2 shear, normal operation
4	SHS	8 m/s, stable/high shear, 10% TI, 0.4 shear, normal operation
5-8	N_{-25}, N_{-10}, N_{+10}, N_{+25}	8 m/s, neutral, 10% TI, 0.2 shear, operation under fixed yaw error
9	N_{Step}	8 m/s, neutral, 10% TI, 0.2 shear, operation with yaw steps

Calibration Approach (Still Being Adapted)

Step	Name	Cases Run	Parameters Calibrated
1	Ambient	N, U, SHS	Eddy viscosity for ambient turbulence (5) & near-wake correction (1) – grouped
2	Shear	S	Eddy viscosity for wake-shear layer (5) – grouped
3	Meander	N, U, S, SHS	Wake diameter (2) & spatial averaging (2) – grouped
4	Fixed Yaw	N_{-25}, N_{-10}, N_{+10}, N_{+25}	Wake deflection (4) – grouped
5	Step Yaw	N_{Step}	Low-pass filter (1)
6	Sweep	N, U, S, SHS	All (20) – independent, for fine tuning

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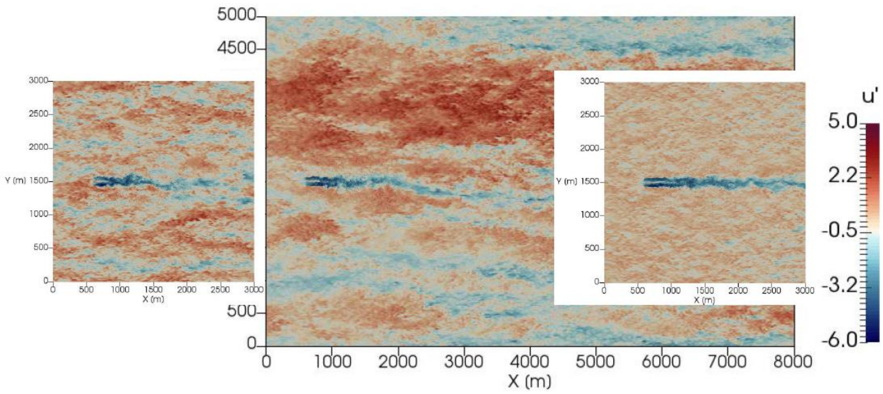
SOWFA Solutions

Neutral
8 m/s, 10% TI, 0.2 shear

Unstable
8 m/s, 10% TI, 0.1 shear

Stable
8 m/s, 5% TI, 0.2 shear

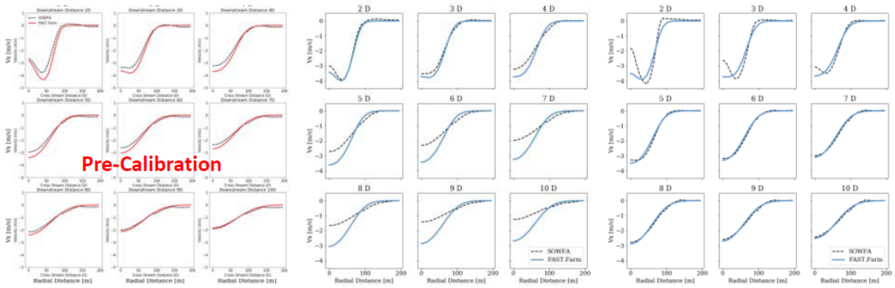


***SOWFA** Solutions*

NATIONAL RENEWABLE ENERGY LABORATORY 8

Intermediate Results (Mid-Calibration)

Neutral *Unstable* *Stable*



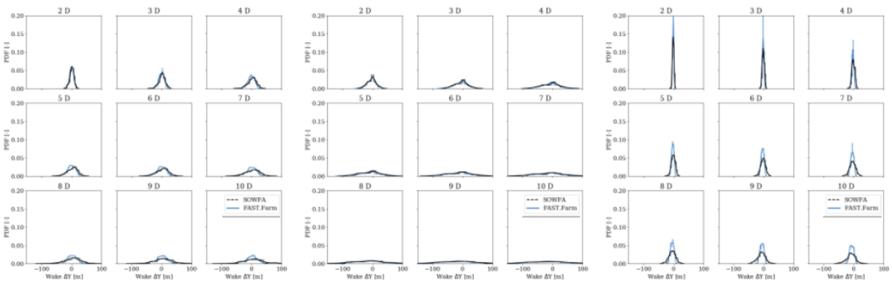
Axial Wake Deficits

- **FAST.Farm** captures change in wake-deficit evolution w/ downstream distance, but doesn't capture change predicted by **SOWFA** across different stability conditions
- Wake-deficit evolution in **FAST.Farm** is strongly influenced by a few calibration parameters – Calibration still in process
- Still reviewing, but think **SOWFA** predicts fast wake recover in U due to anisotropic turbulence
- Results suggest that **FAST.Farm** requires:
  - Different calibration parameters for different stability conditions or
  - Improved physics in the eddy-viscosity formulation

NATIONAL RENEWABLE ENERGY LABORATORY 9

Intermediate Results (Mid-Calibration)

Neutral *Unstable* *Stable*



Horizontal Wake Meandering

- **FAST.Farm** captures overall wake-meandering statistics predicted by **SOWFA** across different stability conditions, w/ slight underprediction for S
  - Meandering in **SOWFA** for S likely driven by more than just large-scale ambient turbulence (e.g. smaller scales or wake-induced turbulence)
- Comparisons hampered by lack of statistical convergence (30-min/case)

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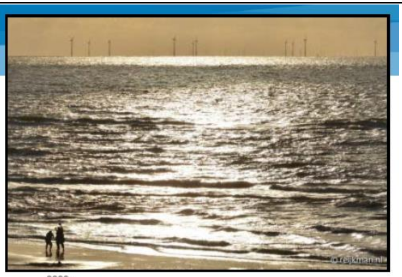
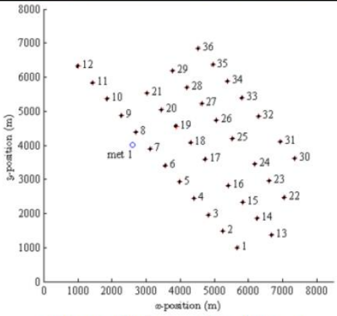
Next Steps

- Complete calibration
- Perform an initial validation of **FAST.Farm** against HFM & data for small wind farms to gain confidence & understand limitations that could be addressed in future
- Release **FAST.Farm** as public, open-source software through **OpenFAST**
- Apply **FAST.Farm** by including turbine loads in wind-farm controls design/testing
- Host a meeting of experts (likely @ TORQUE 2018) to discuss current capabilities & uses of mid-fidelity wind-farm engineering tools such as **FAST.Farm** & to outline their limitations, needs, & future development direction





OWEZ Offshore Wind Farm [Churchfield et al 2014]

Carpe Ventum!

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Deficiencies in modelling approaches that should be improved through future V&V Projects

6/9/2017 Carlos Rodriguez
Senior research engineer

CATAPULT Offshore Renewable Energy

Agenda

- Introduction: how we got here.
- Modelling Levenmouth WT: efforts made so far.
  - Simulated vs. real deflections show noticeable differences.
  - Defining in addition a FAST aero-elastic model.
  - Loads comparison using a subset of critical load cases.
  - Comparing dynamic behaviour between models.
  - Comparing dynamic behaviour vs. SCADA data.
- Conclusions: need for a three way validation and verification task, follow up of CLOWT measurements campaign.
- Corollary: why using Bladed, FAST and HAWC2 in this validation?

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Introduction: how we got here

- ORE Catapult's 7MW Levenmouth demonstration turbine was commissioned in 2012.
- Wind industry has problems to model and simulate similarly large WTs.
- ORE Catapult will carry out a measurements campaign called CLOWT (CLOne of a Wind Turbine), starting on late 2017.
- CLOWT is based on IEC 61400-13 standards.
- CLOWT is meant to expand longer than the usual 6 months (through the whole lifetime of the WT).
- CLOWT is adding further instrumentation for research purposes.
- ORE Catapult will reasonably share this wealth of data for research purposes.
- ORE Catapult is planning to do a three way validation and benchmarking using Bladed, FAST and HAWC2 and comparing them to CLOWT measurements.
- This presentation is showing efforts made in this direction so far.

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Modelling the Levenmouth WT: efforts made so far

- A Bladed aero-elastic model was created to commission this WT.
- We are now validating its structural performance.
- The only reliable data available come from blade tests at Fraunhofer IWES.
- We are then replicating in simulations the same blade test conditions.

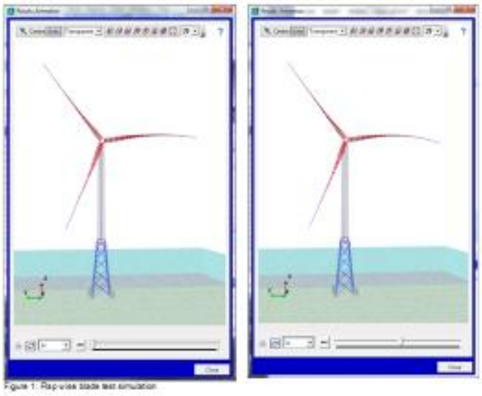

Figure 1: Flap-wise blade test simulation

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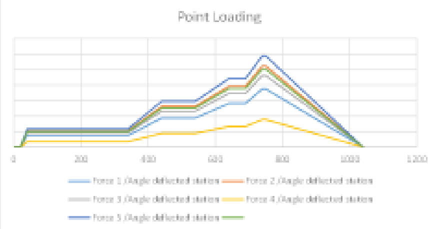
Simulated vs. real deflections show noticeable differences

Same loading from blade tests has been applied to existing Bladed model.



Noticeable differences arise with existing Bladed model.

Channel	Units	Bladed	Fraunhofer	Comparison
Blade 1 y-deflection at 33m	m	#######	##########	12%
Blade 1 y-deflection at 41m	m	#######	##########	18%
Blade 1 y-deflection at 52m	m	#######	##########	15%
Blade 1 y-deflection at 77m	m	#######	##########	16%

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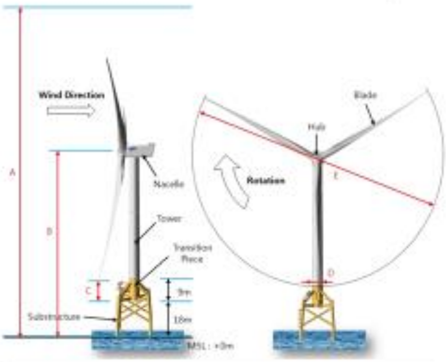
Defining in addition a FAST aero-elastic model

This model has been checked against all main structural properties, including general dimensions, masses, stiffness distributions and eigenfrequencies.



Item	"A"	"B"	"C"	"D"	"E"
-	196.0 m (MSL)	110.6 m (MSL)	7.0 m	7.0 m	171.2 m

"A" is the blade tip height, "B" is the hub height, "C" is the tip clearance, "D" is the diameter of tower bottom, "E" is the rotor diameter, MSL : Mean Sea Level.

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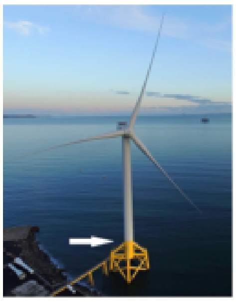
Loads comparison (FAST vs Bladed) using a subset of critical load cases

A selected set of load cases (1.3, 2.2, 2.3, 6.2) has been simulated in FAST and compared to the current loads envelope in transition piece, giving reasonable results.



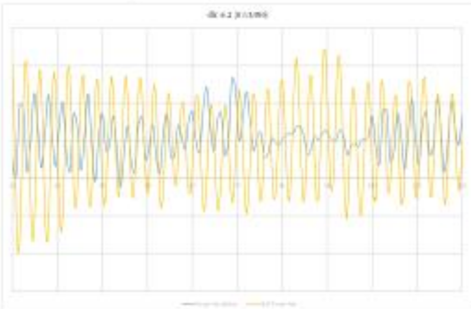
		Load	Mx	My	Mz	Fx	Fy	Fz	Safety
		Cases	kNm	kNm	kNm	kN	kN	kN	factor
Mx	Max	DLC6.2	-75%						1.1
Mx	Min	DLC6.2	-75%						1.1
My	Max	DLC2.2		-15%					1.1
My	Min	DLC2.3		15%					1.1
Mz	Max	DLC1.3			-30%				1.35
Mz	Min	DLC1.3			-30%				1.35
Fx	Max	DLC1.3				0%			1.35
Fx	Min	DLC2.3				10%			1.1
Fy	Max	DLC6.2					-75%		1.1
Fy	Min	DLC6.2					-75%		1.1
Fz	Max	DLC6.2						-10%	1.1
Fz	Min	DLC1.3						-20%	1.35

Comparing dynamic behaviour between models (FAST vs Bladed)

Dynamic behaviour has been compared for power production and idling under identical wind conditions. Factors to take into account:

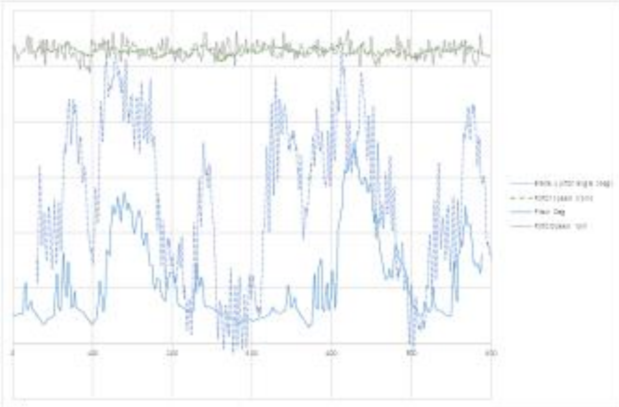
- differences in control (in this case due to IP issues) shall be avoided.
- differences in wind conditions shall be avoided.
- differences in structural definitions/assumptions.

Figure 3. Tower-base coordinate system.



Comparing dynamic behaviour (Bladed) vs. SCADA data

- comparison for pitch and rotor speed.
- similar behaviour for rotor speed, not for pitch.



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Conclusions: need for a three way validation and verification task, follow up of CLOWT measurements campaign

- This is what we are trying to do: translating a real structure into a set of data and then validate that model against real measurements.

Figure 1: Levenmouth Wind Turbine

Figure 2: Aero-elastic model from FAST

- We propose to use Bladed (previously defined for commissioning), FAST and HAWC2 for this purpose.

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Corollary : why using Bladed, FAST and HAWC2 in this validation?

- Bladed is a common tool used in the industry, well proven and validated.
- Bladed has developed a multi-part blade modelling tool to account for very flexible blades.

- FAST is an open source aero-elastic code, widely used in research projects.
- FAST is a counterpart for Bladed's dominant position.
- FAST module 'BeamDyn' accounts for bending-torsion structural coupling.

- HAWC2 has developed a new linear anisotropic beam element implemented into the non-linear aeroelastic multibody.

- None of these has been validated against real measurements on this detail and extension (including tower, foundation and mid-blade sensors, extending measurements for longer than 6 months).

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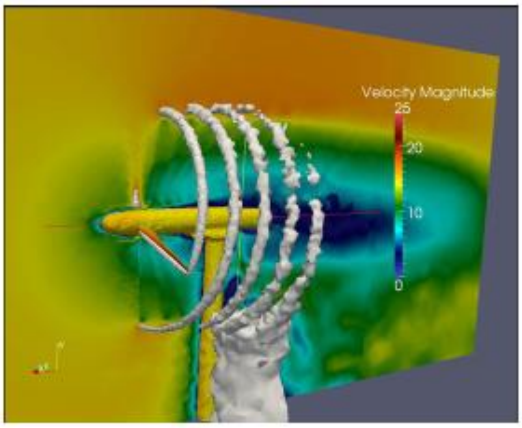
Time for high-fidelity modeling like CFD or 3D FEM?



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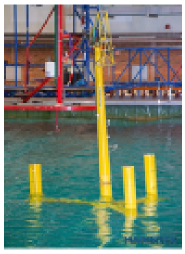
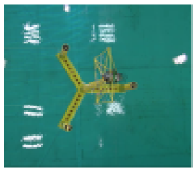
Real-time hybrid model (ReaTHM®) testing of a braceless semi-submersible wind turbine: Experimental approach and validation efforts





Erin Bachynski, NTNU Department of Marine Technology
IEA Task 11, Topical Experts' Meeting 88
Edinburgh, Scotland, September 2017

Model testing of floating wind turbines

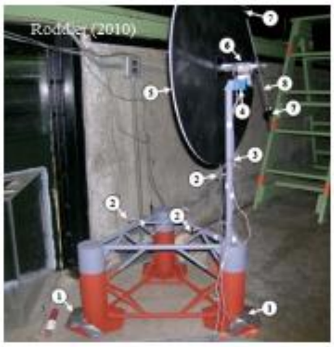
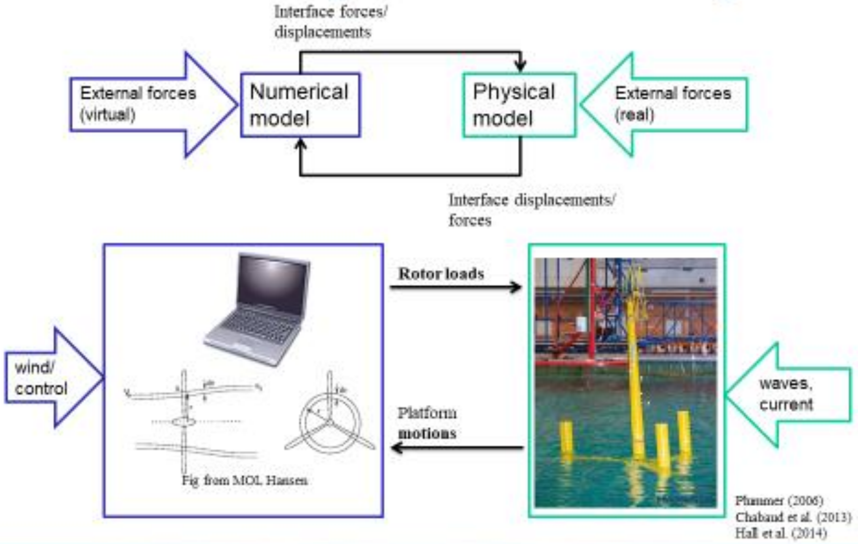


Fig. 1 Images of a) redesigned, thrust-matched blade and b) original geometrically-scaled, NREL 5 MW reference wind turbine blade.

Real-time hybrid model testing



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Advantages of ReaTHM testing

- Physically model aspects which scale well, numerically model those which do not
  - Correctly scaled aerodynamic loads
  - Nonlinearities in hydrodynamics are captured physically
- Reduction of experimental uncertainties
  - Loads which are applied are measured and known
  - State-of-the-art modeling of offshore wind fields
- Flexibility
  - WT controller modifications, fault conditions
- Potential cost reduction
  - Simpler model construction

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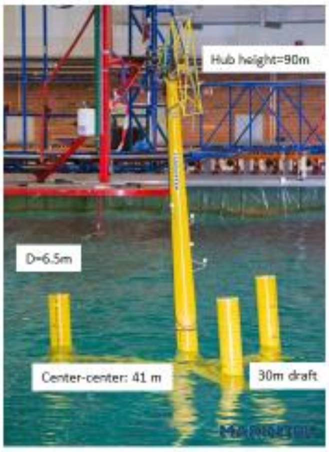
Experimental Setup

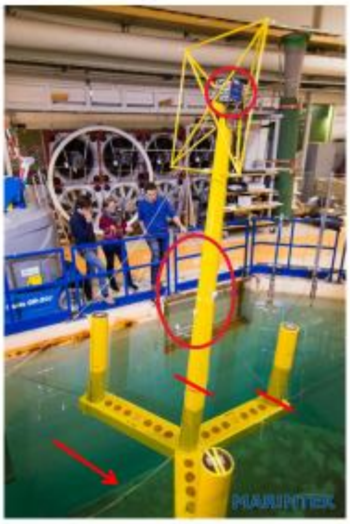
- The FWT:
  - 5MW CSC turbine
  - Floater designed by C. Luan for the NOWITECH project
  - 5 MW NREL rotor-nacelle-assembly
- Froude scale 1/30
- Water depth: 200m
- 3 chain-chain mooring lines
- Tested in the Ocean Basin at SINTEF Ocean (fmr. MARINTEK)

	Specified	Measured	Deviation
Mass (tonnes)	10214	9730	4.7%
VCG (m)	18.9	19.05	0.79%
I_{yy} abt CG (tonne-m^2)	10.16x10^6	10.30x10^6	1.38%
I_{zz} abt CG (tonne-m^2)	8.05x10^6	7.64x10^6	5.12%



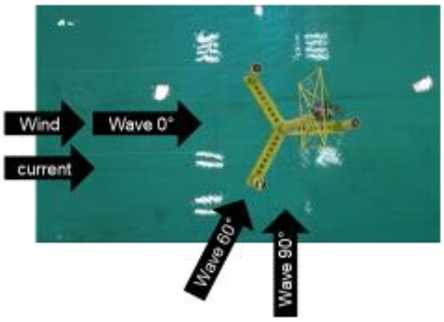
Experimental Setup: Instrumentation

- Optical position measurement
- Linear accelerations and rate of rotation at hub
- "Wind line" and mooring line tensions
- Overturning moment X and Y at base of tower
- Overturning moment X and Y at base of column 3
- Ultra thin instrumentation cable under the model



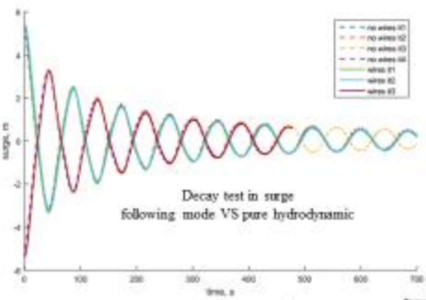
Model Test program

- Tests without hybrid system
  Pullout, Decay, Regular waves, Pink noise, Irregular waves
- Tests in following mode
  Decay, Regular waves, Irregular waves
- Tests with constant wind
  Decay and Regular waves
- Tests with turbulent wind
  - Wind-only
  - Irregular waves
    - Below rated, rated, above rated
    - One test with current
    - Misaligned waves
  - Fault conditions



Step by step increase in complexity with repetitions and decomposed conditions

Assessment of model test method



- Following mode: actuators on, but asked not to disturb.
- Repeatability

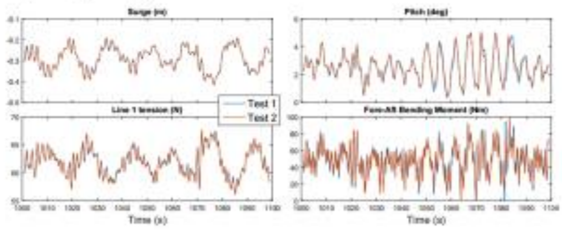
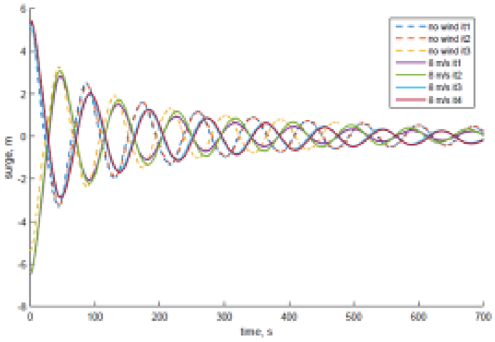


Figure 11.12.: Repeatability, above rated wind speed. Values are in model scale.

Decay Tests – Surge, constant wind



Below rated (8m/s)

- Mean value subtracted for comparison
- Slight increase in damping due to small motions at the nacelle.
- Lengthening of the natural period due to wind forces and torque controller

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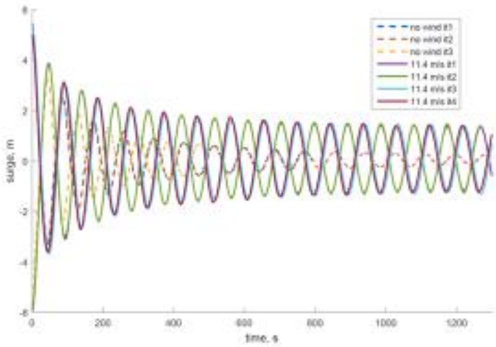
Decay Tests – Surge, constant wind



At rated (11.4m/s)

- Decay reached a limit cycle

⇒Related to the blade pitch controller

- PI controller for blade pitch for a natural frequency of 0.2rad/s (31.4s), slightly below f_n^{pitch} and above f_n^{surge}.

⇒Negative feedback

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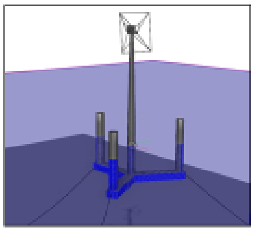
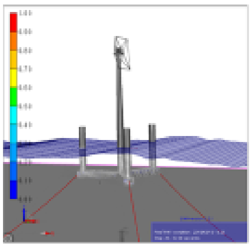
Braceless Semi-submersible – initial global numerical model





Parameter	Description	Model
Numerical model	Fully coupled time domain Rigid body / Elastic mooring	SIMA
Waves	Irregular waves (3hrs)	Time series from experiment
Wind loads	Normal turbulence model class B Kaimal wind spectrum Rigid rotor blades	Resultant force as applied in ReaTHM tests: TurbSim + Aerodyn GDW
Potential flow loads	Radiation • Added Mass • Damping • Memory effect Diffraction Hydrostatic stiffness Drift forces	• Panel model (WAMIT) • Convolution integral • Newman's approximation
Viscous loads	Flow separation	Strip theory (Morison)
Mooring lines	Stationkeeping Restoring forces	Non-linear FEM Bar elements

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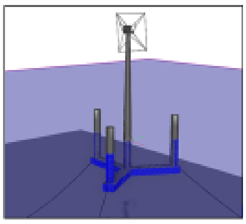
From model test results to calibrating numerical model



	Description
Mooring system	i. Pretension ii. Static (pull-out test) iii. Dynamic response
Decay tests	i. Natural periods ii. Damping
Waves Only	i. Regular ii. Pink Noise iii. Irregular
Wind only	i. Steady ii. Unsteady
Wave and wind	Combined

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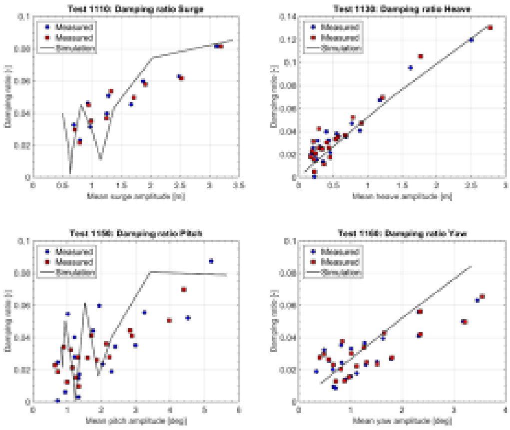
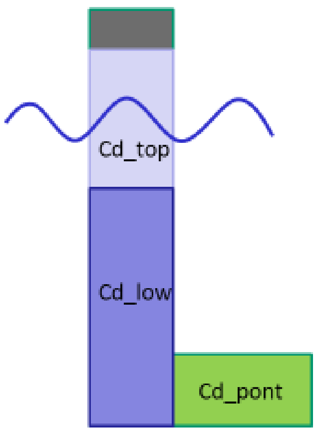
Decay tests – Calibration of Cd-values

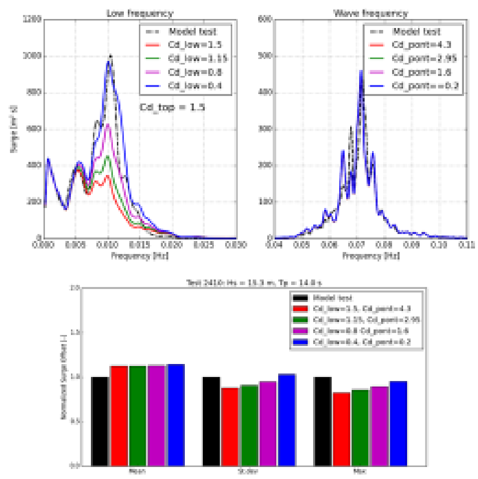
- Step-by-step
  - Heave: pontoons
  - Surge: column
  - Check yaw & pitch



	Cd-value
Column	0.5
Pontoon	4.3

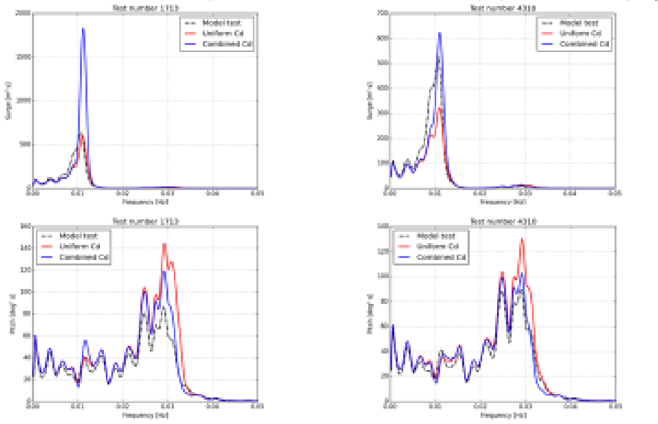
Irregular waves – Calibration of Cd values





Wind only vs wind and waves

W=11.0 m/s W=11.0 m/s, Hs=3.6 m, Tp=10.2 s



Results show that coefficients calibrated in calm water do not perform well when waves are present (too much damping, not enough excitation force).
-Increase Cd near splash zone -> more wave excitation
-Reduce Cd further below -> decreased damping

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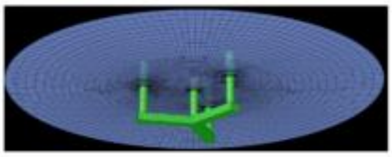
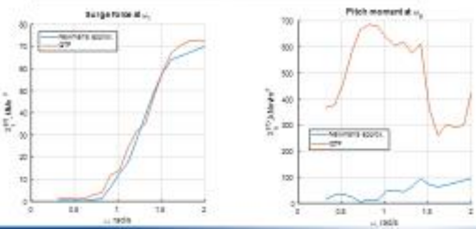
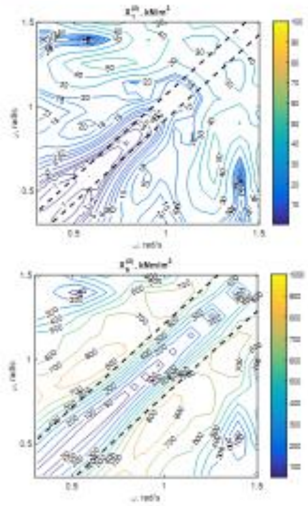
Effects of 2nd order potential

Three models for the hydrodynamic loads due to potential flow:

(1): SIMA 1Order: 1st order potential flow, no drift forces;
(2): SIMA 1OrderDrift: 1st order potential flow plus drift forces according to Newman's approximation;
(3): SIMA QTF: 1st order potential flow plus second order difference-frequency forces from the full QTF.







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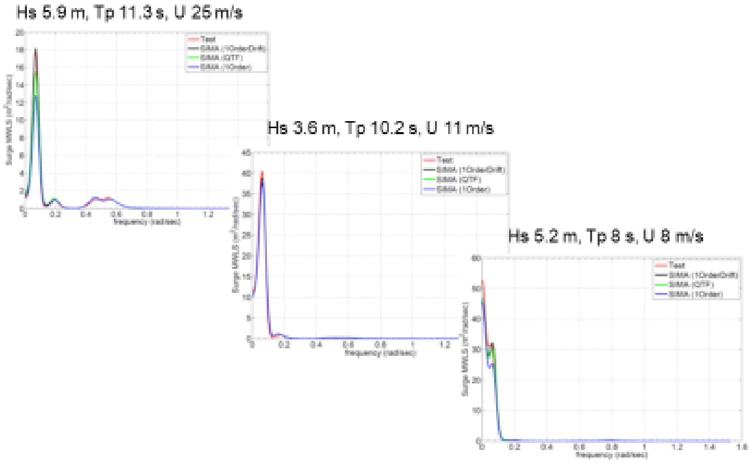
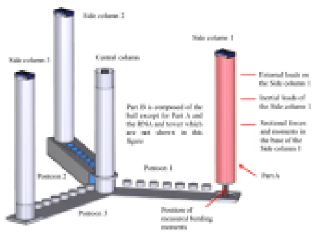
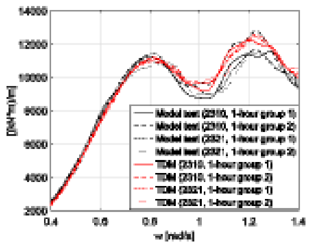


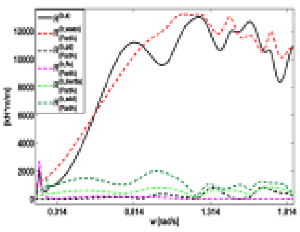
- Challenge: effect of second order potential and effect of viscous drag loads is easily confused
- Frequency resolution of QTF vs Newman's approximation also makes a difference

Internal loads in the hull

- Multibody modelling method (Luan and Moan 2017)
- Good agreement for bending moment transfer function from pink noise tests (up to 1.4 rad/s)
- Numerical tool suggests excitation force is dominant for this cross section (not true for all)







Conclusions

- Successful demonstration of ReaTHM testing for FWTs
- Numerical models give generally good agreement
  - Low-frequency motions depend strongly on drag coefficients
  - Drag coefficient depends on wave characteristics
  - Little effect of 2nd order potential flow model for this floater
  - Aerodynamic loads should be applied based on numerical simulation (to avoid mixture of damping/excitation forces)
  - Multibody model approach gives good estimate of internal loads in the hull
- Challenges remain
  - Application of identical aerodynamic loads in test and simulation
  - Higher-frequency effects
  - Flexibility in blades and floater
  - Highly nonlinear hydrodynamic loads
  - Validation of aerodynamic models
  - Internal loads on sections which are more sensitive to radiation, wind

Publications

- Bachynski, E. E.; Chabaud, V. & Sauder, T. Real-time hybrid model testing of floating wind turbines: sensitivity to limited actuation. *Energy Procedia*, **2015**, *80*, 2-12
- Sauder, T.; Chabaud, V.; Thys, M.; Bachynski, E. E. & Sæther, L. O. Real-Time Hybrid Model Testing of a Braceless Semi-submersible Wind Turbine: Part I: The Hybrid Approach. *35th International Conference on Ocean, Offshore and Arctic Engineering*, **2016**
- Bachynski, E. E.; Thys, M.; Sauder, T.; Chabaud, V. & Sæther, L. O. Real-Time Hybrid Model Testing of a Braceless Semi-Submersible Wind Turbine: Part II: Experimental Results. *Proceedings of the ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering*, **2016**
- Berthelsen, P. A.; Bachynski, E. E.; Karimirad, M. & Thys, M. Real-time Hybrid Model testing of a Braceless Semi-submersible Wind Turbine. Part III: Calibration of a Numerical Model. *35th International Conference on Ocean, Offshore and Arctic Engineering*, **2016**
- Chabaud, V. Real-Time Hybrid Model Testing of Floating Wind Turbines
  Norwegian University of Science and Technology, Norwegian University of Science and Technology, **2016**
- Karimirad, M.; Bachynski, E. E.; Berthelsen, P. A. & Ormberg, H.
  Comparison of real-time hybrid model testing of a braceless semi-submersible wind turbine and numerical simulations
  Proceedings of the 36th International Conference on Ocean, Offshore and Arctic Engineering, **2017**
- Luan, C.; Gao, Z. & Moan, T.
  Development and verification of a time-domain approach for determining forces and moments in structural components of floaters with an application to floating wind turbines
  Marine Structures, **2017**
- Luan, C.; Chabaud, V.; Bachynski, E. E.; Gao, Z. & Moan, T.
  Experimental validation of a time-domain approach for determining sectional loads in a floating wind turbine hull subjected to moderate waves
  Energy Procedia, **2017**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This research is part of FME NOWITECH (Norwegian Research Centre for Offshore Wind Technology) which is funded by the Research Council of Norway, industrial companies and participating research organizations
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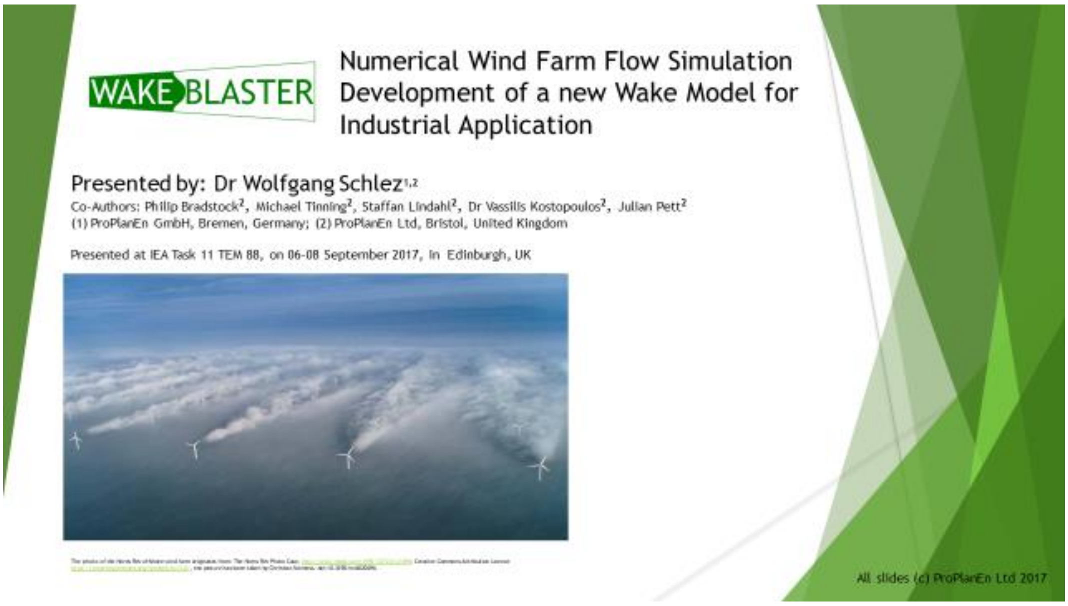
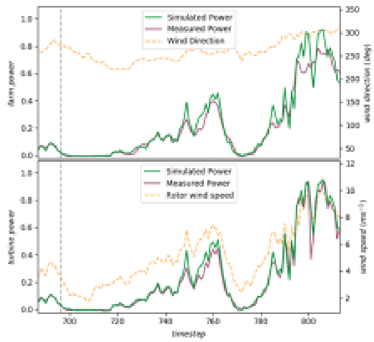

WAKE BLASTER
Numerical Wind Farm Flow Simulation
Development of a new Wake Model for Industrial Application
Presented by: Dr Wolfgang Schlez1,2
Co-Authors: Philip Bradstock2, Michael Tinning2, Staffan Lindahl2, Dr Vassilis Kostopoulos2, Julian Pett2
(1) ProPlanEn GmbH, Bremen, Germany; (2) ProPlanEn Ltd, Bristol, United Kingdom
Presented at IEA Task 11 TEM 88, on 06-08 September 2017, in Edinburgh, UK
All slides (c) ProPlanEn Ltd 2017

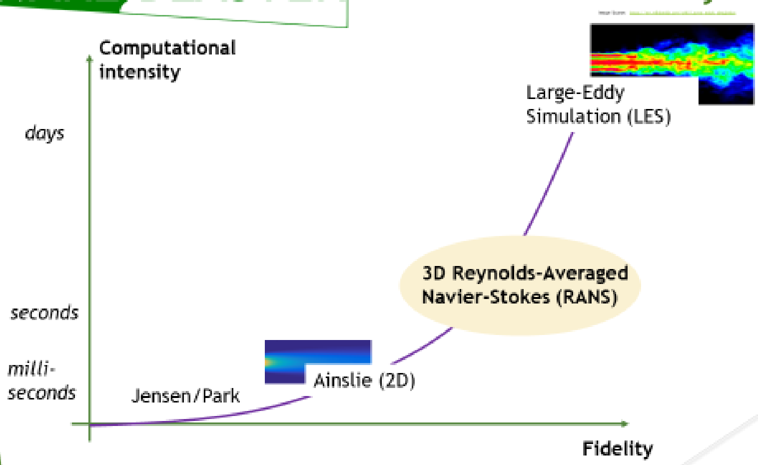
WAKE BLASTER Time Domain Simulation

Challenge:

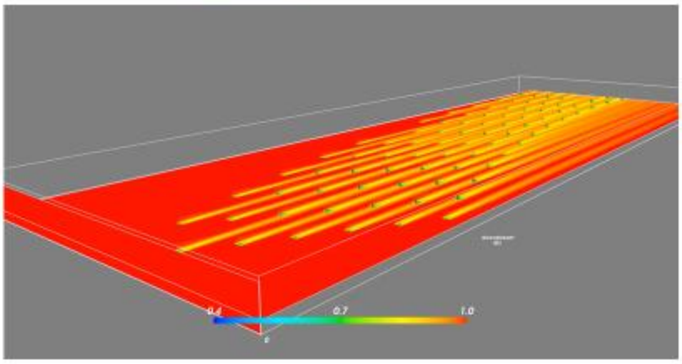
- Accurate time-domain calculation of wind farm performance (diurnal, seasonal, …)
- Individual turbines react to environmental or technical curtailments.
- Accurate turbine performance considering hysteresis, turbulence, density, curtailments.
- Direct use of measured meteorological data.
- Simulation of development phases, curtailments and maintenance cycles.
- Target is industrial application.



WAKE BLASTER Wake Model Fidelity

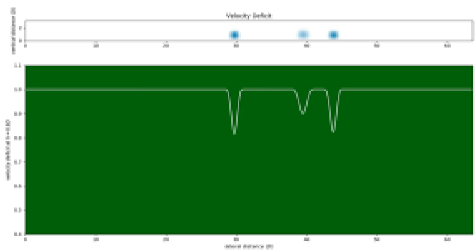


WAKE BLASTER 3D wake model



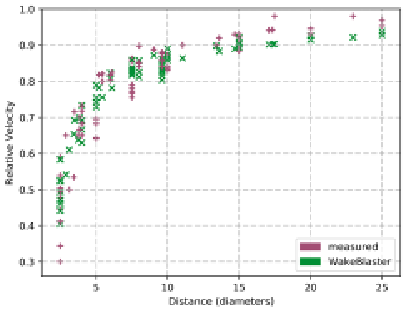
- WakeBlaster development includes a 3D CFD solver of RANS equations.
- Real-time performance even with large wind farms.

WAKE BLASTER Wake superposition



- Each turbine introduces a individual wake into the flow field.
- Wake superposition and merging are fully modelled by the 3D solver.

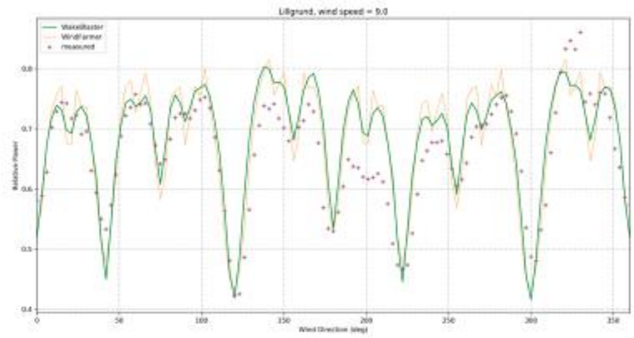
WAKEBLASTER Validation



Wake centreline velocity deficit - development downstream of a wind turbine. Multiple validation cases (+) and WakeBlaster simulation (x)

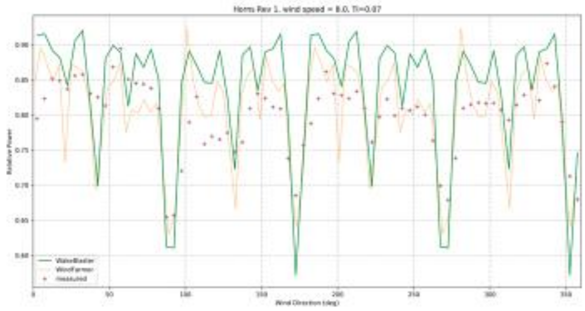
- Working with several partners providing historical SCADA data
- > 25 years of wind farm data
- > 15 wind farms
- > 450 wake scenarios prepared
- Offshore and onshore

WAKEBLASTER Validation (preliminary)



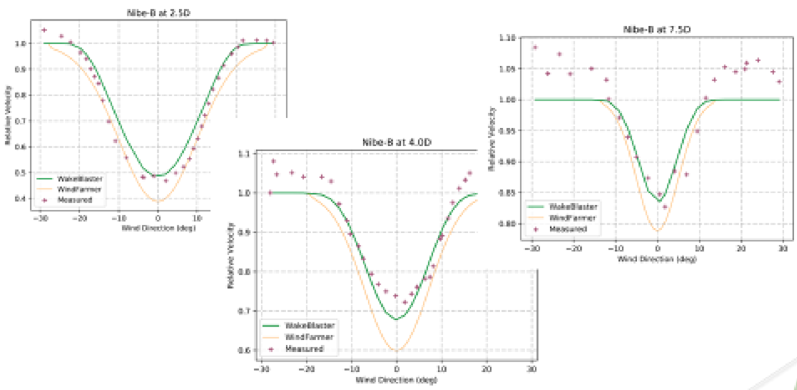
360 degree view of wind farm performance for Lillgrund offshore wind farm - WakeBlaster, WindFarmer and SCADA data compared

WAKE BLASTER Validation (preliminary)

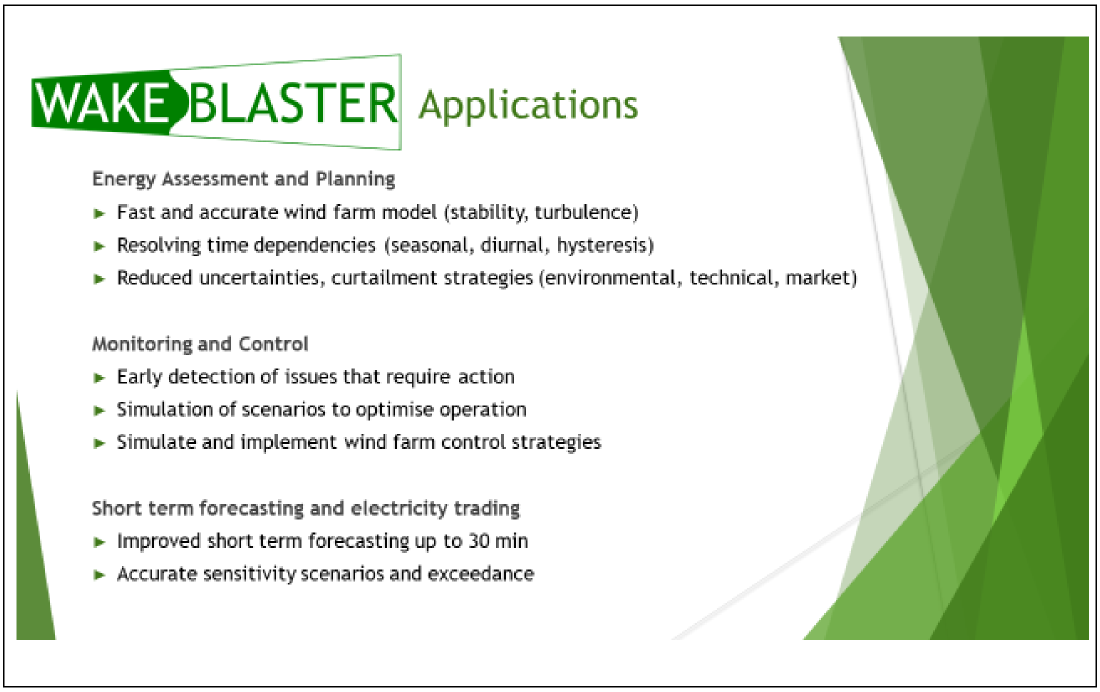


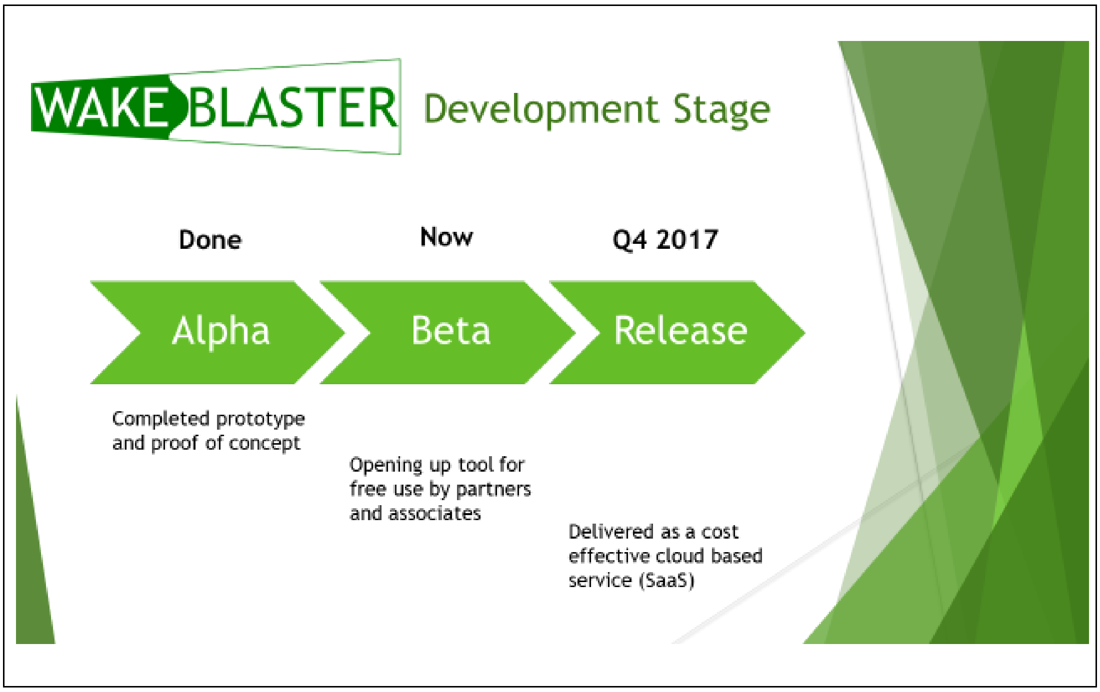
360 degree view of wind farm performance for Horns Rev offshore wind farm - WakeBlaster, WindFarmer and SCADA data compared

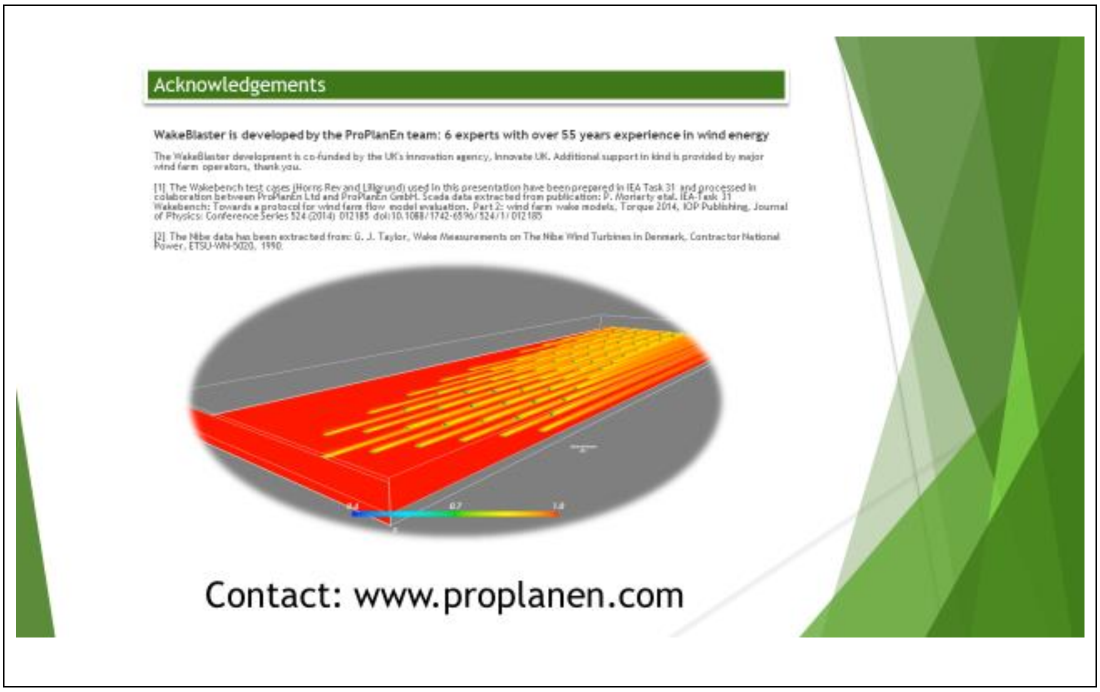
WAKE BLASTER Validation (preliminary)

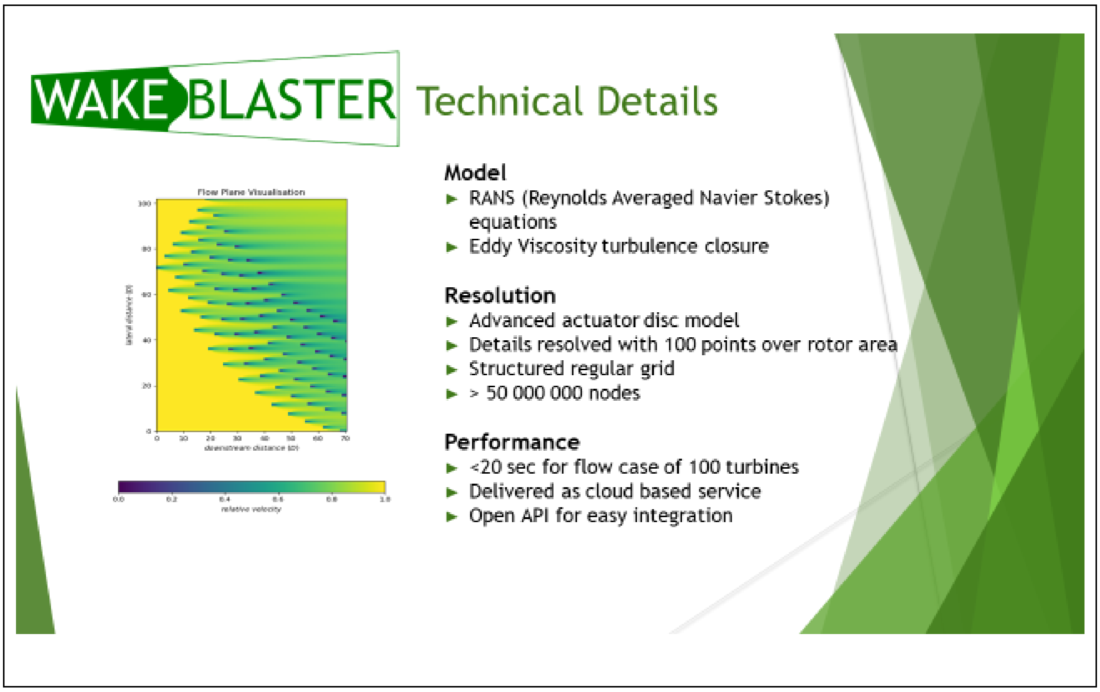


WakeBlaster results compared to relative velocity profile at Nibe [2] for downstream distances 2.5, 4.0 and 7.5 D.


WAKE BLASTER
Applications
Energy Assessment and Planning
Fast and accurate wind farm model (stability, turbulence)
Resolving time dependencies (seasonal, diurnal, hysteresis)
Reduced uncertainties, curtailment strategies (environmental, technical, market)
Monitoring and Control
Early detection of issues that require action
Simulation of scenarios to optimise operation
Simulate and implement wind farm control strategies
Short term forecasting and electricity trading
Improved short term forecasting up to 30 min
Accurate sensitivity scenarios and exceedance


WAKE BLASTER
Development Stage
Done
Now
Q4 2017
Alpha
Beta
Release
Completed prototype and proof of concept
Opening up tool for free use by partners and associates
Delivered as a cost effective cloud based service (SaaS)


Acknowledgements
WakeBlaster is developed by the ProPlanEn team: 6 experts with over 55 years experience in wind energy
The WakeBlaster development is co-funded by the UK's innovation agency, Innovate UK. Additional support in kind is provided by major wind farm operators, thank you.
[1] The Wakebench test cases (Horns Rev and Lillgrund) used in this presentation have been prepared in IEA Task 31 and processed in colaboration between ProPlanEn Ltd and ProPlanEn GmbH. Scada data extracted from publication: P. Moriarty et.al. IEA-Task 31 Wakebench: Towards a protocol for wind farm flow model evaluation. Part 2: wind farm wake models. Torque 2014, IOP Publishing, Journal of Physics: Conference Series 524 (2014) 012185 doi:10.1088/1742-6596/524/1/012185
[2] The Nibe data has been extracted from: G. J. Taylor, Wake Measurements on The Nibe Wind Turbines in Denmark, Contractor National Power, ETSU-WN-5020, 1990.
Contact: www.proplanen.com


WAKE BLASTER Technical Details
Flow Plane Visualisation
Model
RANS (Reynolds Averaged Navier Stokes) equations
Eddy Viscosity turbulence closure
Resolution
Advanced actuator disc model
Details resolved with 100 points over rotor area
Structured regular grid
> 50 000 000 nodes
Performance
<20 sec for flow case of 100 turbines
Delivered as cloud based service
Open API for easy integration

DNV·GL

Experience from Verification of New BEM Implementation in the Bladed Code

The Need for Further Validation of Dynamic Stall Theory

6 September 2017

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Experience from Verification of New BEM Implementation in the Bladed Code

- Contents:
  - New Bladed Aerodynamics
  - Dynamic Stall
  - Results differences to old Bladed Aerodynamics
  - The primary causes for results differences
  - Recommendations for further validation and verification

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New BEM Implementation in the Bladed Code

- **Modernise aerodynamic formulation in Bladed**
  - source code re-written using modern technology
  - More rigorous handling of 3D geometry, coning, blade sweep etc.
- **Additional theoretical models including a skew-wake correction providing a restoring yawing moment in cases with yaw misalignments**
- **Allow aerodynamics to be linearised.**
  - Increase accuracy of linearisation for control design
  - Pre-requisite for blade stability analysis

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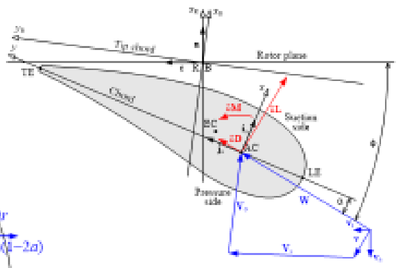
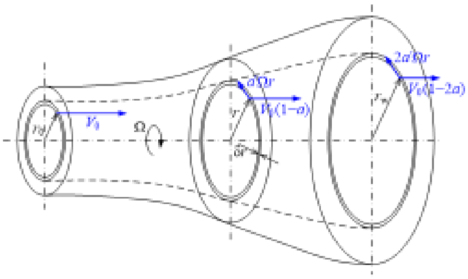
Bladed 4.8 Aerodynamics

- The fundamentals of Blade Element and Momentum theory are well established
- However there is lots in the detail





- For example:

  Bladed 4.8 Aerodynamics includes the structural deflection in the calculation of section orientation

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Dynamic stall model – Attached flow Theodorsen's Theory

- Theodorsen, working at NACA wrote a paper in 1934 on solving the linearised potential flow loading solution for a flat plate aerofoil with a flap
- The aim was the understanding of the phenomenon known as flutter

Theodore Theodorsen
(January 8, 1897 – November 5, 1978)

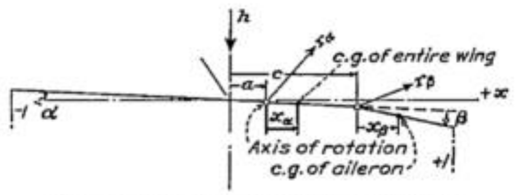


FIGURE 2.—Parameters of the airfoil-aileron combination.

Bladed 4.8 Aero Implementation – Dynamic Stall 1

- The Beddoes Leishman models are based on a combination of work from Risø(1) and Leishman (2)
- State-Space representation of the approximation of the Wagner function:
  - $\dot{x}_1 + \frac{\left(b_1 + \frac{c\dot{U}}{2U^2}\right)x_1}{T_u} = \frac{b_1 A_1 \alpha_{3/4}}{T_u}$
  - $\dot{x}_2 + \frac{\left(b_2 + \frac{c\dot{U}}{2U^2}\right)x_2}{T_u} = \frac{b_2 A_2 \alpha_{3/4}}{T_u}$
  - $T_u = \frac{c}{2U(t)}$

Where:
- $\dot{x}_n$ attached flow state (rate)
- A_n, b_n Coefficients and exponents of indicial functions
- U Local wind speed (including induction, and structural motion)
- $\alpha_{3/4}$ angle of attack at quarter chord position

- With the attached flow states an effective angle of attack is determined:

$$\alpha_E = \alpha_{3/4}(1 - A_1 - A_2) + x_1 + x_2$$

- The attached normal force coefficient is then found as:
- $C_N^{Circ\_att} = Cn_\alpha(\alpha_E - \alpha_0)$

1 Hansen, M.H., Gaunaa, M., and Madsen, H.Aa., "A Beddoes-Leishman type dynamic stall model in state-space and indicial formulations". Technical report Risø-R-1354(EN), Risø National Laboratory, Roskilde, June 2004

2 G. Leishman, State-Space model of unsteady airfoil behaviour and dynamic stall, In Center for Rotorcraft Education and Research, 1989

Dynamic stall model – Trailing edge stall

- The model of stall is a specific case of Kirchoff flow – characterised by regions of stagnant air with potential flow around them
- The value of normal force is approximated as

$$C_N = 2\pi\left(\frac{1+\sqrt{f}}{2}\right)^2 \alpha$$

- Where f is defined as the separation and obtained from the steady aerofoil data

Gustav Robert Kirchhoff

(12 March 1824 – 17 October 1887)

Bladed 4.8 Aero Implementation – Dynamic Stall 2

- Time lagged interpolation between fully attached and fully separated flow

$$\dot{x}_3 + \frac{x_3}{T_p T_u} = \frac{Cn_\alpha(\alpha_e - \alpha_0) + \pi T_u \dot{\alpha}}{T_p T_u}$$

$$\dot{x}_4 + \frac{x_4}{T_f T_u} = f^{st}\left(\frac{x_3}{Cl_\alpha} + \alpha_0\right)$$

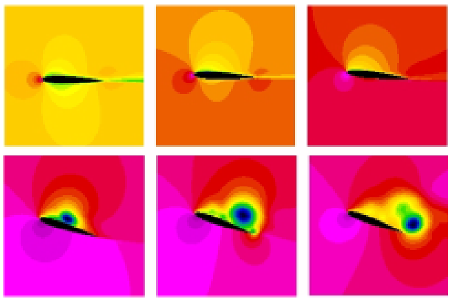
- Where:
  - T_p Pressure lag constant (user input in Bladed)
  - T_f Separation position constant (user input in old & new aerodynamics)
- The dynamic normal force coefficient then is expressed as:

$$Cn^{dyn} = Cn_\alpha(\alpha_E - \alpha_0)x_4 + Cn^{fs}(\alpha_E)(1 - x_4) + \pi T_u \dot{\alpha}$$

- Where:
  - Cn^{fs} Normal force coefficient for fully separated flow

Dynamic stall model – Leading edge stall

- The most severe kind of stall
- Pressure becomes so high at the leading edge that a vortex forms and detaches
- Sudden increase in lift and drag followed by sudden loss of lift
- Wind turbine aerofoils are designed with the aim of avoiding this phenomenon
- The model used is described in the paper "A Semi-Empirical Model for Dynamic Stall" by Leishman and Beddoes from 1986



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Bladed New Aero Implementation – Dynamic Stall 3

- A vortex lift term is added, which only kicks in in case there is a rapid ramp to stall
- The model is expressed in Cn,Cc rather than Cl,Cd but for the drag coefficient the Cd is calculated explicitly
- Impulsive lift/moment states are available for the compressible model. However these are high frequency -> slower simulations

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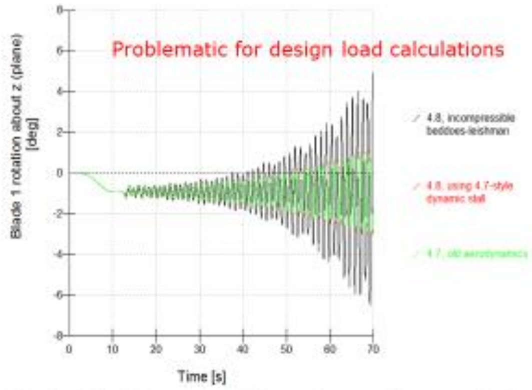
Comparing results with old Bladed aerodynamics



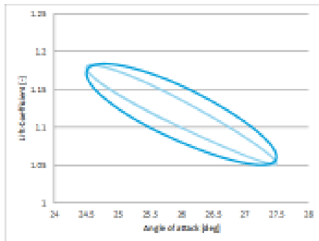
Blade parked, wind direction = 30°, wind speed = 50 m/s, structural damping = 0%

Results differences – Dynamic stall model

- Difference 1

Pre-4.8 formulation (Kirchoff) $Cn = Cn_\alpha \left(\frac{1+\sqrt{f}}{2}\right)^2 (\alpha - \alpha_0)$

4.8 aerodynamics $Cn = Cn_\alpha(\alpha - \alpha_0)f + Cn^{fs}(\alpha)(1-f)$

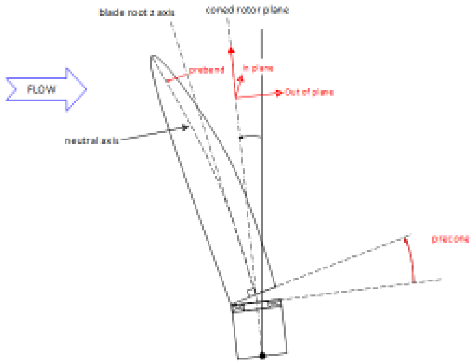


comparison in unsteady lift coefficient of new aerodynamics, α= 26º + 1.5º*sin(1.257πt), V_∞=50m/s, c=1m

- Difference 2: Vortex lift term (leading edge stall)
  - pre-4.8 formulation remains active in deep stall
  - New Aero term is inactive in deep stall

Results differences – Simplified aerofoil orientation

- In pre-4.8 aerodynamics the blade inflow conditions are computed relative to the coned rotor plane.
- This means aerofoil orientation due to do blade bending is excluded. (except for torsion)
- In Bladed 4.8 the inflow conditions are computed relative to the neutral axis including all structural deformations of the blade.
- This difference in assumptions can lead to significant loading results in extreme conditions.



Other differences in the implementations

- Three quarters cord position
- Mach number
- $\frac{c\dot{U}}{2U^2}$ term in attached flow dynamics

Recommendations for future work

- Currently design standards do not specify which aerodynamic models to use. Together with industry/academics and certifying bodies it is recommended to:
  - Define recommended practises for BEM modelling
    - Assumptions on correction methods for yaw/shear
    - Recommended dynamic wake models
    - Assumptions on computing inflow conditions.
  - Improve dynamic stall models in deep-stall conditions.
    - Tune existing dynamic stall models against CFD/wind tunnel measurements
    - Develop new engineering models that capture unsteady aerodynamics in deep stall

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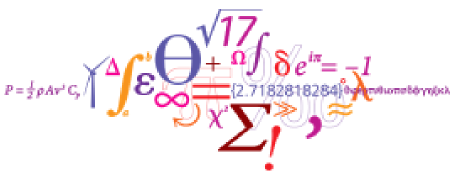
Aeroelastic code validation
- A mixed collection of examples

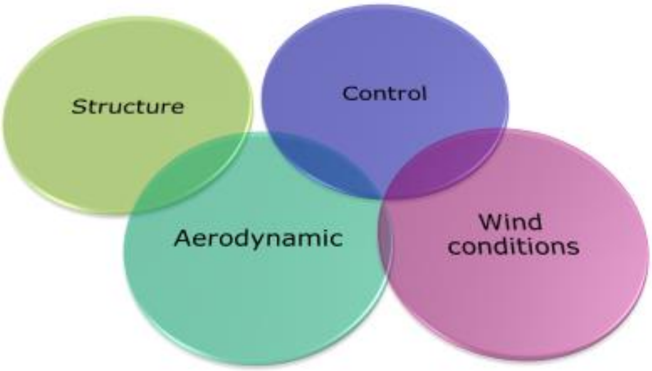
Torben J. Larsen

IEA Wind Task 11
Scotland 06.09.2017



DTU Wind Energy
Department of Wind Energy

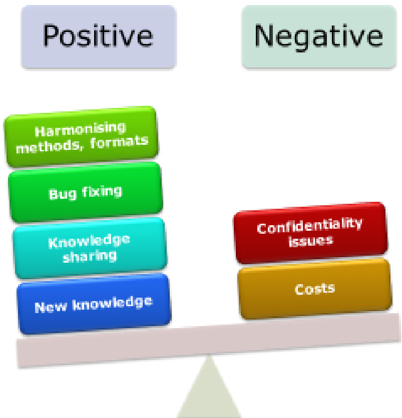
The four load drivers



We can choose to focus on individual areas, but all has to be OK for the loads to be correct

2 DTU Wind Energy, Technical University of Denmark 05 September 2017

What do we want to achieve?



- Code-2-code comparison
  - Codes of same complexity level
  - Codes of varying complexity
- Code-2-controlled experiments
  - Eg wind tunnel experiments
  - Floating wind turbine tests
- Code-2-fullscale experiments
  - Wind turbine level
  - Wind farm level

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OC3, OC4, (OC5) Code-2-code

- Public fictive reference turbine generated
- Comparing in steps. Start simple – advance gradually
- Comparison possible also for new types of concepts
- Great for knowledge sharing, interesting discussions
- Enabled a much bigger community within (relevant) wind turbine load simulations

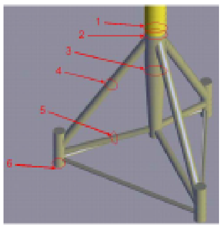


Figure 2. *Tripod load output positions*

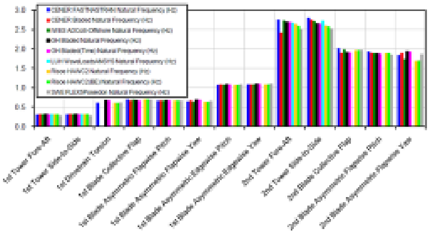


Figure 20. Full-system natural frequencies from load case 1.2

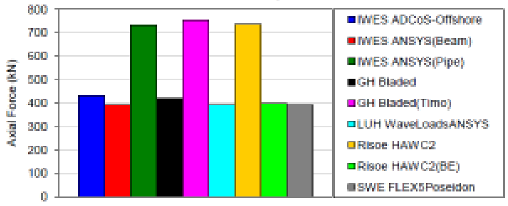
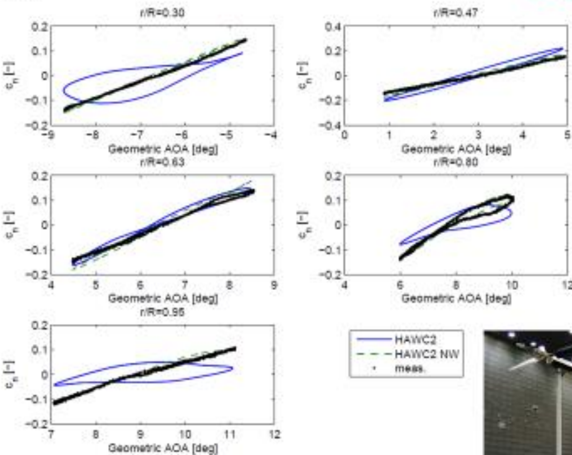


Figure 18. *Axial force 10 m under MSL in the central column of the tripod (location 3 as described in Figure 2)*

Dedicated experiments

- NREL/NASA phase VI experiment
- Example of Stand still situation with pitching blades
- Pitch amplitude 2deg
- Wind speed 23.3m/s

- Comparison with HAWC2 results and HAWC2 with a nearwake model



Trailed vorticity modeling for aeroelastic wind turbine simulations in stand still

Georg R. Pirrung, Helge Aa. Madsen, and Scott Schreck

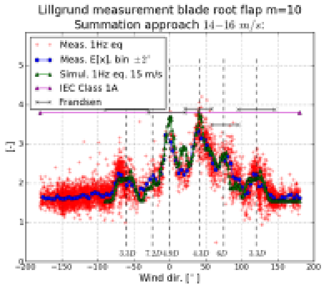
Previous results Lillgrund - 2015

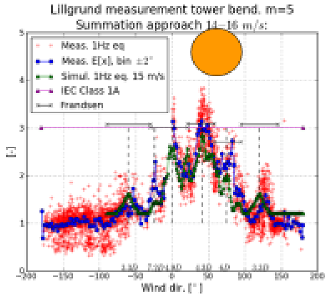
EWEA 2015 PARIS

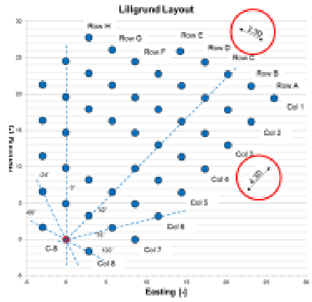
17 - 20 November 2015 | Porte de Versailles Pavilion 1, Paris, France

Wake effects above rated wind speed. An overlooked contributor to high loads in wind farms.

T.J. Larsen, G. Larsen, H.A. Madsen and S.H. Petersen







14-16m/s

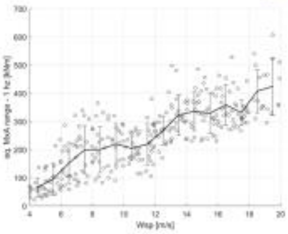
- Generally a very good to excellent agreement is seen
- High wind speed situations are highly important
- What happens in the "outlier" situations?

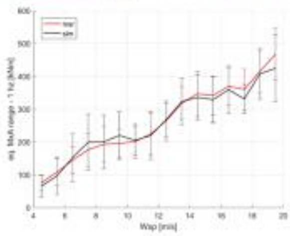
DTU Wind Energy, Technical University of Denmark

05 September 2017

The V52 DTU test facility

- Fully instrumented V52 turbine (pitch, speed, power, strain gauges, accelerometers)
- Met mast in western sector
- LIDAR in nacelle in upwind configuration
- Inflow with 5-hole pitot tube
- Spinner anemometer
- Aeroelastic model
- Ongoing project for creating one-2-one sim/meas comparisons





West North East South

Increasing the wind field information

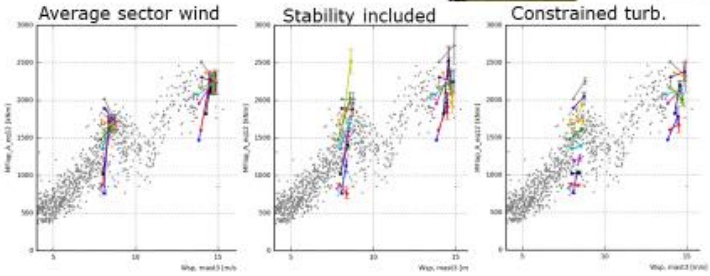
Siemens SWT 3.6MW Tjæreborg

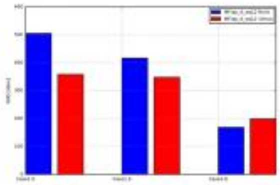
Pitot tube installed on one blade

Free wind information derived based on pitot measurements and an inverse induction model

Courtesy: Siemens Wind Power

Mads M. Pedersen, DTU Wind Energy

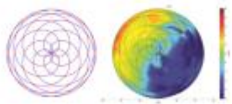




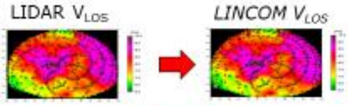
05 September 2017

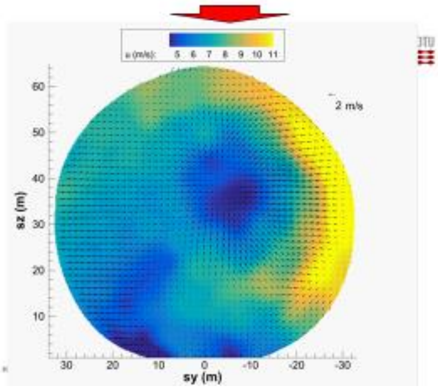
Spinner LIDARS provide unique options

- Lidars techniques evolves very quickly
- DTU Spinner LIDAR scans a full disc in 2 sec (LOS)
- Using a linearized flow solver a good estimate of u,v,w components can be found
- This could remove most of the uncertainty related to the windfield



$$U\frac{\partial u}{\partial x}+V\frac{\partial u}{\partial y}+W\frac{\partial u}{\partial z}=-\frac{\partial}{\partial x}\frac{p}{\rho}+K_{H}\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right]+K_z\frac{\partial^2 u}{\partial z^2}$$
$$U\frac{\partial v}{\partial x}+V\frac{\partial v}{\partial y}+W\frac{\partial v}{\partial z}=-\frac{\partial}{\partial y}\frac{p}{\rho}+K_{H}\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right]+K_z\frac{\partial^2 v}{\partial z^2}$$
$$U\frac{\partial w}{\partial x}+V\frac{\partial w}{\partial y}+W\frac{\partial w}{\partial z}=-\frac{\partial}{\partial z}\frac{p}{\rho}+K_{H}\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right]+K_z\frac{\partial^2 w}{\partial z^2}$$
$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$





Courtesy: Mikkel Sjøholm,

Torben Mikkelsen

DTU Wind Energy

DTU

Summary

- Code 2 code validation
  - Very good for knowledge sharing
  - Great for bug fixing
  - Testing of details that may be difficult to test in experiments
  - Cost are low
  - Reference is missing
- Code 2 controlled experiments
  - Often new knowledge
  - Mexico, New Mexico
  - Test of floating wind turbines
- Code 2 controlled experiments
  - New knowledge and understanding
  - Focus on details
  - The big picture is missing
  - Issues with scaling, Re numbers, boundary effects etc.
- Full scale experiments
  - Excellent for new knowledge
  - All aspects included
  - Costly, confusing, confidentiality issuess
  - New flow measurement options may bring it closer to a controlled experiment!

10 DTU Wind Energy, Technical University of Denmark 05 September 2017

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Introduction to Break-Out Sessions

Jason Jonkman, Ph.D.

IEA Wind Task 11 TEM #88
September 6-8, 2017
Edinburgh, Scotland

CATAPULT
Offshore Renewable Energy

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

- Three 1.5-hour break-out sessions
- Within each session, split into three groups in terms of topic areas where future IEA Wind collaborative(s) involving three-way V&V between data, HFM, and engineering models are possible:
  - Wind-farm aerodynamics – Lead: Pat Moriarty
  - Rotor aero-elastics – Lead: Helge Madsen
  - Offshore hydrodynamics – Lead: Amy Robertson
- Within each group, discuss pathways and prioritization for establishing future IEA Wind V&V collaborative(s)
- Participants can switch groups between sessions if desired

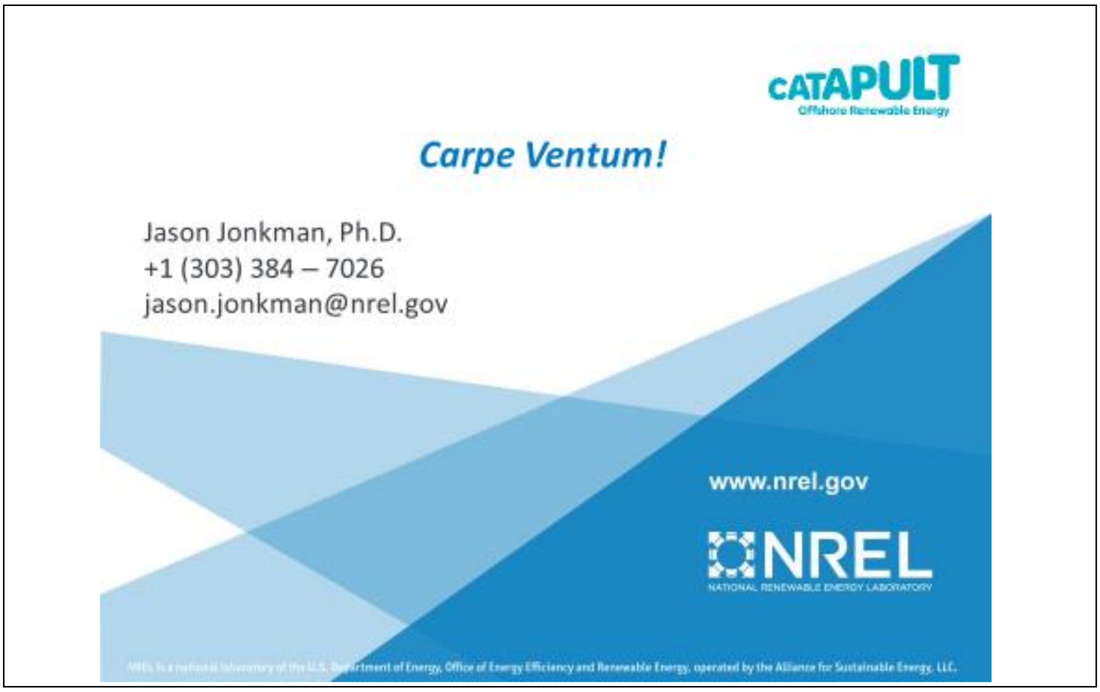
NATIONAL RENEWABLE ENERGY LABORATORY 53

Questions to Guide the Discussion

- Fundamental question – Should IEA Wind establish one or more collaborative(s) involving three-way V&V between data, HFM, and engineering models and what could that look like?
- Related questions:
  - Where is the greatest uncertainty & conservatism in existing models limiting technology improvement?
  - What level of model fidelity (HFM <-> engineering models) is needed in each technology development step?
  - How can HFM be used to develop/calibrate/validate engineering models?
  - Can surrogate models be a good substitute for physics-based engineering models?
  - What physical insights should be targeted by HFM & experimentation?
  - What relevant experimental datasets are available & what data is still needed?
  - Is V&V of HFM done in conjunction with, or before, engineering model V&V?
  - Should V&V focus on steady-state (e.g. power) or time-resolved (e.g. loads) physics?
  - What metric should be used to quantify validation success or failure?
  - What is the role of UQ in the V&V effort?
  - What are the long-term goals of the collaborative(s)?
  - What should be the initial focus of the collaborative(s)?
  - Who and with what software are interested in participating in the new collaborative(s)?
  - Should the new collaborative(s) proceed as extensions of IEA Wind Task 29 (MexNext), IEA Wind Task 30 (OC5), &or Task 31 (WakeBench) or should new collaborative(s) be initiated?

NATIONAL RENEWABLE ENERGY LABORATORY 54


Break-Out Session Group Locations
3rd Floor
2nd Floor
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
Break out 2
Break out 1
2.1
2.2
2.3
Catering room
Main room
RECEPTION
& OFFICES
NATIONAL RENEWABLE ENERGY LABORATORY


CATAPULT
Offshore Renewable Energy
Carpe Ventum!
Jason Jonkman, Ph.D.
+1 (303) 384 – 7026
jason.jonkman@nrel.gov
www.nrel.gov
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Comprehensive Field Measurements on Research Turbines and Large Prototypes

Dr. Christian Kress

IEA Wind Task 11 | Topical Expert Meeting #88
Edinburgh, United Kingdom, 7 September 2017

Fraunhofer IWES

Outline

- Fraunhofer Institute for Wind Energy and Energy System Technology (IWES North West)
- Application Center for Wind Energy Field Measurements
- Field Measurement Expertise
- Field Measurements on Research Turbine in Project “Smartblades 2”
- Field Measurements on 180m-rotor-diameter Prototype Adwen AD 8-180 at Fraunhofer test site

Fraunhofer IWES

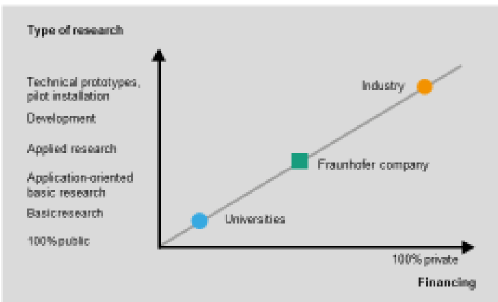
Short Profile of Fraunhofer IWES North-West

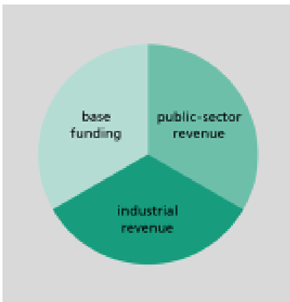
Managing Director	Prof. Dr.-Ing. Andreas Reuter
Research spectrum	Wind energy from material development to grid connection
Operational budget 2016	€ 16.8 million
Staff	160 employees
Located in	Bremerhaven, Oldenburg, Bremen, Hanover
Investments to date in the establishment of infrastructure	€ 80 million
Research Alliance Wind Energy	Strategic Alliance with ForWind and the German Aerospace Center (DLR)

Fraunhofer IWES

Fraunhofer's Business Model: Focus on Industry as a Factor for Success

- 67 Fraunhofer Institutes in Germany
- More than 24,000 employees, mainly with an academic background in natural or engineering sciences
- € 2.1 billion annual research budget





Fraunhofer IWES

Accelerated Time to Market through Realistic Testing

Rotor blade test hall for up to 90-meter-blades

- Testing of design prototypes prior to series production
- Max. static bending moment 115,000 kNm; max. dynamic bending moment: +/- 30,000 kNm

DyNaLab with 10 MW drive performance / peak 15 MW

- Nominal torque: > 8.6 MNm
- Rotor load application unit for dynamic bending moments, thrust and radial forces
- Artificial grid: 44 MVA installed inverter power

Support structure test center

- Testing of fatigue behavior of foundations and support structures
- Scale 1:10 to 1:3.5

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Fraunhofer IWES´s Application Center for Wind Energy Field Measurements

- Expertise in performing customized field measurements on wind turbines
  - Field test campaigns tailored to turbine, site and project
  - Measurements in wind farms, on prototypes & research turbines
- Management of research projects involving field measurements
- Accredited test and calibration laboratory for field measurements (according to ISO/IEC 17025)
- Staff of 6 scientific employees

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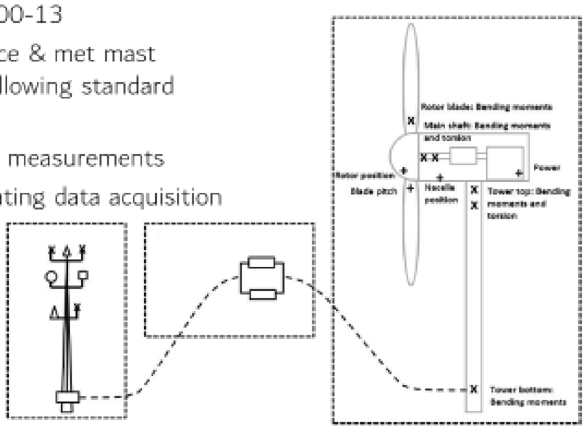
Application Center for Wind Energy Field Measurements

Customized Measurements on Operating Wind Turbines

- Mechanical load measurements following standard IEC61400-13
- Power performance & met mast measurements following standard IEC61400-12-1
- Lidar & met mast measurements
- Customized operating data acquisition



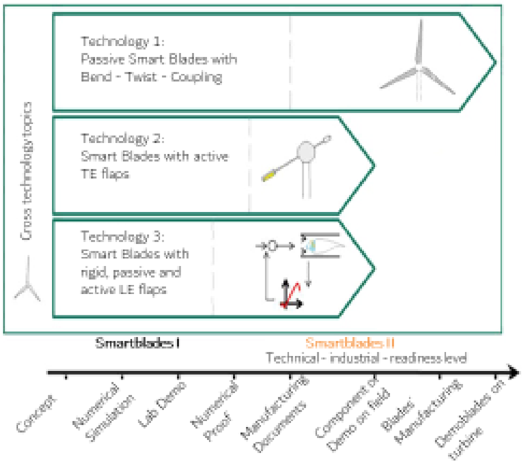
 7 Fraunhofer IWES

Projects "Smart Blades I & II"

Supported by: Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag

Goal: Reduction of loads by means of smart blades.

- ➢ Reduction of the COE
- ➢ Proof of concept based on numerical and lab results
- ➢ Field test on demonstrators
- ➢ Validation of simulation tools



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Supported by: Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag

Project "Smart Blades II"

- Joint project of **Research Alliance Wind Energy** of Fraunhofer IWES, German Aerospace Center and ForWind Alliance
- Involvement of major OEMs and suppliers

Research Alliance	Industry Partners
Fraunhofer IWES	SUZLON
ForWind	SENVION
DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.	EMERSON, SSB Wind Systems
Research Alliance Wind Energy	ENERCON
	Henkel
	GE
	NORDEX

Supported by: Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag

Project "Smart Blades II"
Manufacturing of Bend-Twist-Coupled Blades

- 20-meter-blades are currently manufactured at German Aerospace Center in Stade, Germany
- Novel instrumentation to detect aeroelastic behavior in field experiments is integrated into blade structure during manufacturing


Source: forschungsverbund-windenergie.de


Source: DLR

Project "Smart Blades II"
Test Bench Evaluation of First Blade at Fraunhofer IWES

- First bend-twist-coupled blade will be tested in Fraunhofer rotor blade test facility
- Test of structural integrity under extreme loads and fatigue load testing according to IEC 61400-23
- Test of integrated blade instrumentation
- Test bench results used for numerical code validations


© Photo Martina Buchholz

Fraunhofer IWES

Project "Smartblades II"
Field Measurements on Research Turbine

- 3 bend-twist-coupled blades will be tested for several months test period
- Measurements refer to:
  - Performances
  - Loads and deformations
  - Wind field
  - Blade sectional inflow


Source: iwes.fraunhofer.de

Fraunhofer IWES

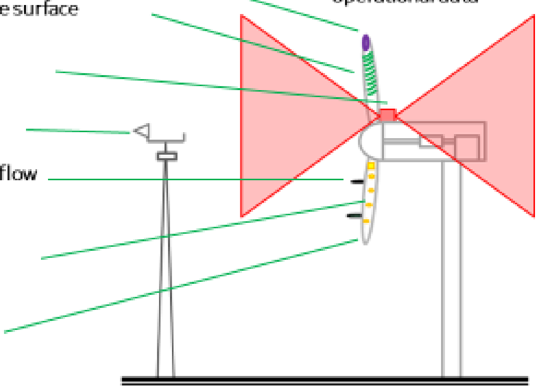
Supported by: Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Project "Smart Blades II"

Instrumentation during Field Measurements

- Novel, multi-axes blade tip sensor
- Flow visualization on blade surface
- Lidar (with upstream and downstream orientation)
- Met mast measurments
- Measurement of incident flow
- Optical blade deflection / distorsion measurments
- Strain measurements
- Noise measurements
- Turbine performance & operational data



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Supported by: Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Project "Smartblades II"

Aerodynamic Flow Measurements during Field Tests

- Pneumatic 5-hole probes at leading edge at 2 spanwise positions to measure inflow angles and velocity
- Measurement system tailored to match blade and turbine specifications
- Remotely controlled measurement system
- Parallel visualization and analysis of flow field on blade surface

Aerodynamic measurement system

Fraunhofer IWES

Project "Smart Blades II"
Intended test campaign in 2018/2019

Supported by: Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag

Test cases:

- Power production with and without rotor in yaw
- Non-optimum tip speed ratios
- Idling / parked conditions
- Start-up and (emergency) shutdown
- Situations of transient pitch and yaw variation

Fraunhofer IWES

World´s Largest Wind Turbine Prototype installed on Fraunhofer IWES Test Site in Bremerhaven, Germany

- Site offers similar-to-offshore wind conditions in vicinity of Fraunhofer facilities
- Earlier tests on Fraunhofer´s dynamic nacelle test bench are validated through field measurements
- Grid connection between prototype and Fraunhofer test facilities

Fraunhofer IWES

180m-Diameter 8MW Wind Turbine Shall be used for Wide Range of Field Experiments

- Following commissioning prototype will be available for unique large-scale field experiments:
- Possible projects:
  - Assessment of blade´s aero-elastic behavior
  - Numerical code validation for next-generation offshore wind turbines
  - Development of efficient maintenance strategies

Fraunhofer IWES

Reliable Field Instrumentation of 88m Wind Turbine Blade

- Fraunhofer´s **Application Center for Wind Energy Field Measurements** shall provide field instrumentation for largest offshore turbines
- Goal is to measure loading along full blade span
- Parallel measurement of aerodynamics (e.g. radial migration, incidence, pressure distribution)

Fraunhofer IWES

Acknowledgements

Federal Republic of Germany

Federal Ministry for Economic Affairs and Energy

Federal Ministry of Education and Research

European Regional Development Fund (ERDF):

Federal State of Bremen

- Senator of Civil Engineering, Environment and Transportation
- Senator of Economy, Labor and Ports
- Senator of Science, Health and Consumer Protection
- Bremerhavener Gesellschaft für Investitions-Förderung und Stadtentwicklung GmbH

Federal State of Lower Saxony

Free and Hanseatic City of Hamburg

Federal Ministry for Economic Affairs and Energy

Federal Ministry of Education and Research

European Union Investing in Bremen's Future European Regional Development Fund

Bremen Bremerhaven

Lower Saxony

Hamburg

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Fraunhofer IWES

Thank You For Your Attention

Questions?

Dr. Christian Kress
christian.kress@iwes.fraunhofer.de

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Back-up

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MARIN

NEW MODEL TESTS FOR V&V OF HFM AND ENGINEERING TOOLS

By Sebastien Gueydon (MARIN)
In collaboration with Erin Bachinsky (NTMU), Amy Robertson (NREL)

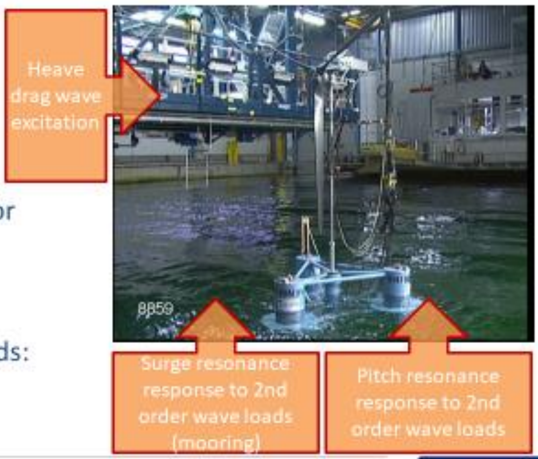
OUTLINE

- OC4 floating foundation
- What we've learnt from previous tests
- Remaining questions on MT and on NS
- New model-tests for V&V of NS focussing on hydrodynamics
- Illustrations of V&V

OC4 SEMISUBMERSIBLE FLOATING FOUNDATION

PREVIOUS CAMPAIGNS

- What has been learnt from the study of these MT and NS



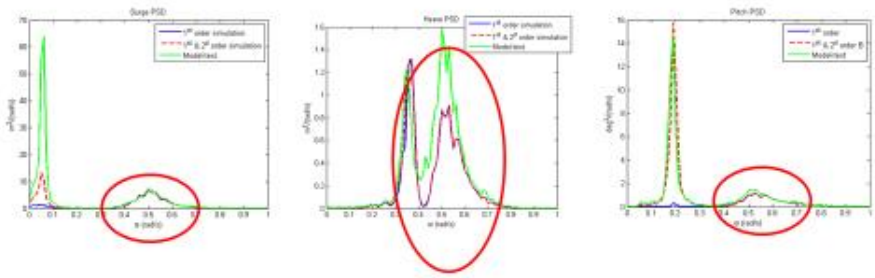
Recommendations for OC4-semi:
- Viscous loads
- Full QTF
- 2nd order wave loads:
  - Horizontal
  - Vertical

4

MARIN

VERIFICATION OF HYDRODYNAMIC RESPONSE

- Operational sea, head waves



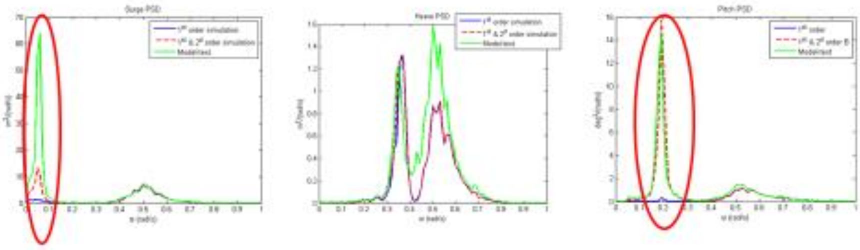
- Response in wave energy range (1st order)

5

MARIN

VERIFICATION OF HYDRODYNAMIC RESPONSE

- Operational sea, head waves



- Response in low frequency range (2^{nd} order)

6

MARIN

THERE ARE STILL QUESTIONS?

- Large underestimation of surge drift loads?
- Importance of drag loads on a floater made of elements of different shapes and dimensions (braces, columns, heave plates)?
- Accuracy of measurements? Accuracy of the Simulations?

7

MARIN

FOCUS ON THE HYDRODYNAMICS

- Response of a Semisubmersible Floating Foundation with special attention to:
- The drag loads
- The wave loads
- The viscous damping
- The accuracy of model-tests / numerical simulations

8 MARIN

NEW MODEL-TESTS

Set-up	Constrained (0 deg pitch)	Constrained (5 deg pitch)	Spring moored
Current (towing tests)	1, 2, 3 m/s	-	-
Surge forced oscillations	{10 m, 100 s} {4 m, 12.1 s} {4 m, 7 s}	- - -	- - -
Regular wave	{7.1 m, 12.1 s} {4 m, 9 s}	{7.1 m, 12.1 s} -	{7.1 m, 12.1 s} {4 m, 9 s}
Irregular waves	{7.1 m, 12.1 s, gamma} White Noise {7.1 m, 6-26 s}	{7.1 m, 12.1 s, gamma} -	{7.1 m, 12.1 s, gamma} White Noise {7.1 m, 6-26 s}
Decays	-	-	Surge, heave, pitch
Restoring	-	-	Surge

9 MARIN

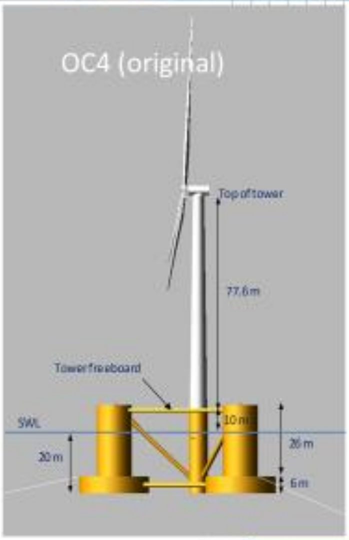
MODEL OF OC6-SEMISUBMERSIBLE

Simplified mooring:

- 3 spring-lines (pre-tensioned)

- Differences?
  - (2017) OC6-SEMI
  - (2013) OC5-SEMI

⇒ "Model of the model"



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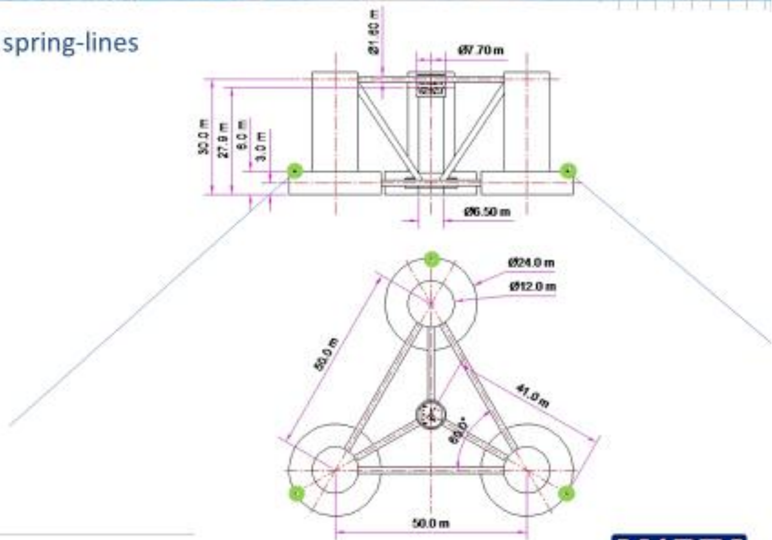
MODEL OF OC6-SEMISUBMERSIBLE

- 3 spring-lines



11

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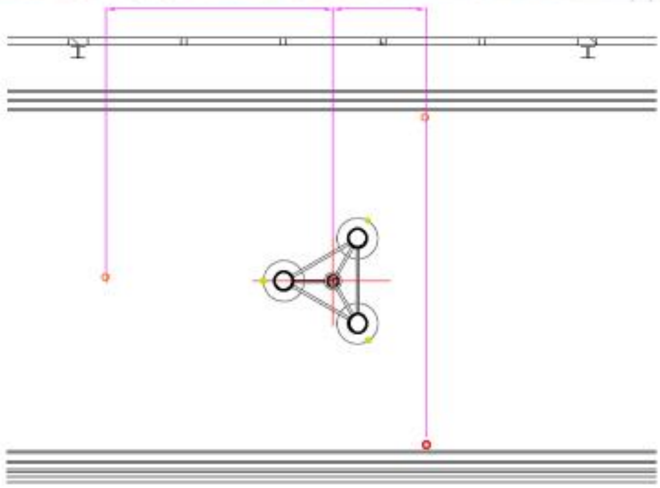
MOORING SYSTEM IN CB



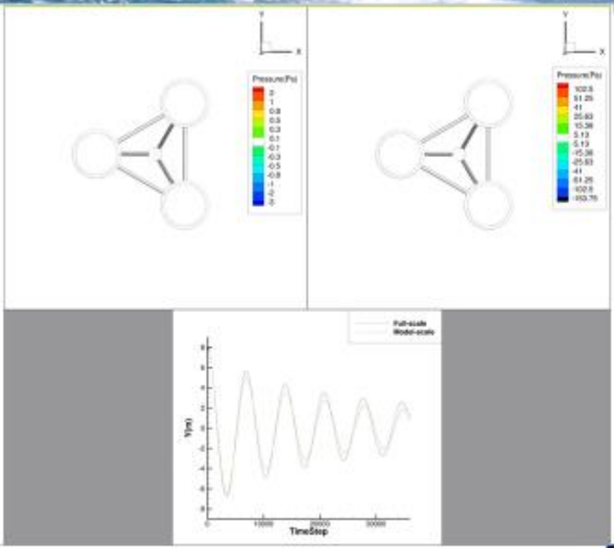
MARIN

GOALS

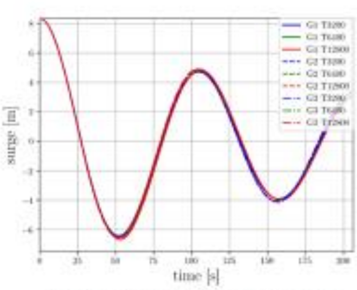
- Simpler system than OC5:
  - No turbine
  - No catenary lines (lying on the floor of the basin) but spring-lines
  - Easier access to the set-up and model
  - But aiming at equivalent inertia properties, equivalent stiffness
- More steps (& data) to compare MT with HFM
  - Captive tests in waves: wave excitation
  - Towing tests: current and drag loads
  - Oscillation tests: drag excitations at given frequencies
- Evaluation of uncertainties of MT and NS
  - Accuracy of measurement devices
  - Repetitions to assess repeatability and quality of process

MARIN

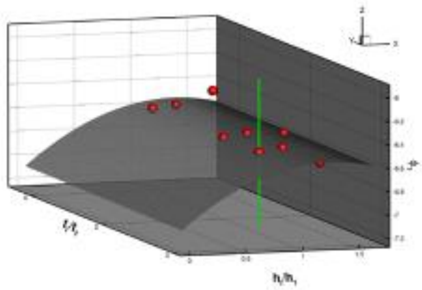
SWAY DECAY TEST OF THE OC5 SEMISUBMERSIBLE



NUMERICAL SENSITIVITY STUDY



(a) Time history of surge motion.



(b) Numerical uncertainty estimation.

Simon Burmester (NUTTS 2017)

CHALLENGE OF DOING MODEL TESTS

Scaling issues, accuracy of devices, cables and human intervention (decay)

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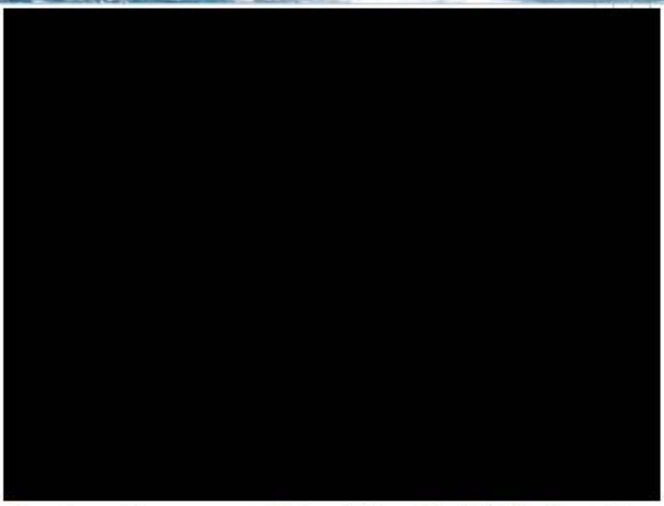
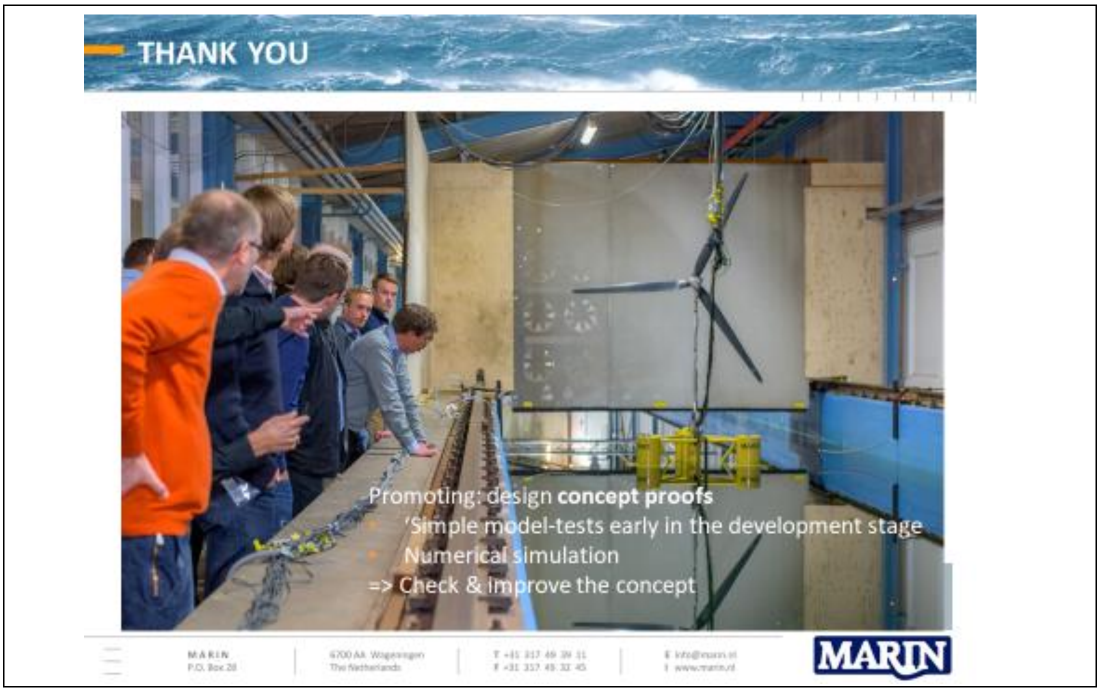
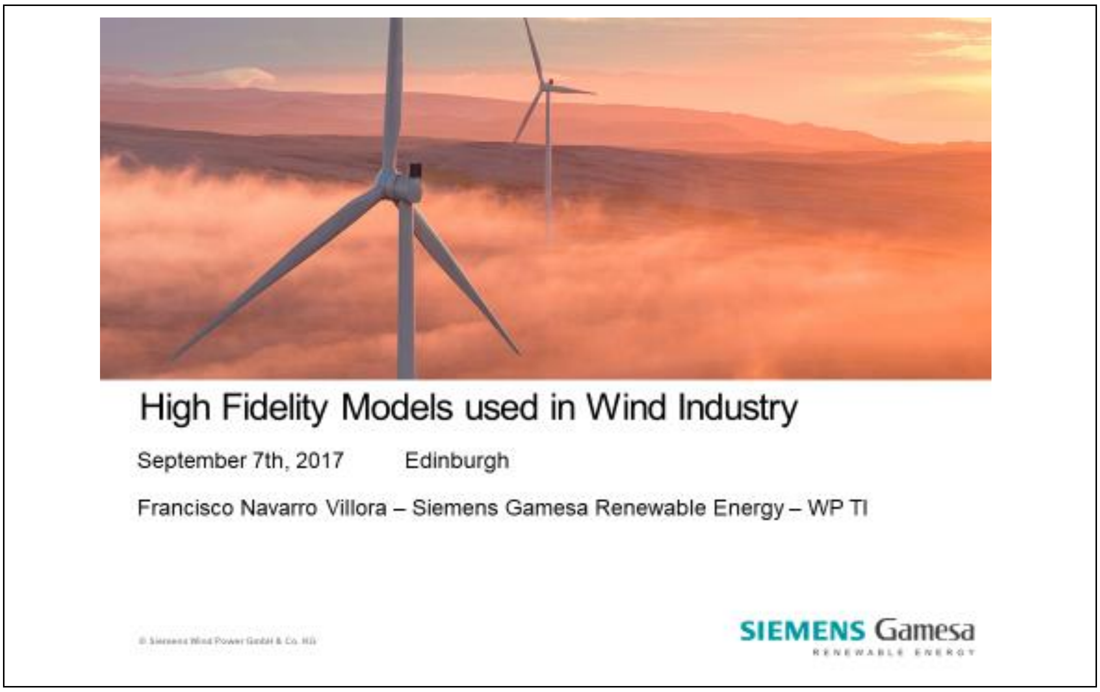
EXPERIMENTS & NUMERICAL SOLUTIONS



Wave impact on a monopile foundation with CFD (Tim Bunnik)

17 MARIN


THANK YOU
Promoting: design concept proofs
'Simple model-tests early in the development stage
Numerical simulation
=> Check & improve the concept
MARIN


High Fidelity Models used in Wind Industry
September 7th, 2017 Edinburgh
Francisco Navarro Villora – Siemens Gamesa Renewable Energy – WP TI
SIEMENS Gamesa
RENEWABLE ENERGY

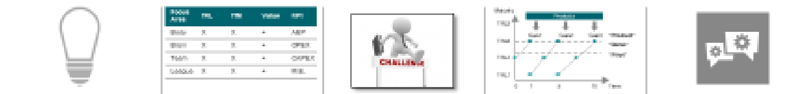
Siemens Gamesa Renewable Energy – Agenda

- Introduction Technology & Innovation
- Modelling Philosophy in Wind Industry
- Wake steering as HFM
- Examples of models with different degree of fidelity

SIEMENS Gamesa RENEWABLE ENERGY

Siemens Gamesa Renewable Energy – Technology & Innovation

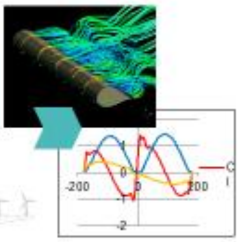
Idea generation	Innovation Portfolio	Expert Consultation	Innovation Roadmaps	Development Plans
Idea collection from industry / university / experts	Innovations gathered and sorted per Innovation Field into the Innovation Portfolio	Expert Consultation provides qualitative evaluation	• Innovation Roadmap assembled • Path to Commercialization: Business impact identified	• Technology & product development defined: TDP & PDP



SIEMENS Gamesa RENEWABLE ENERGY

Siemens Gamesa Renewable Energy – Modelling Philosophy

• Traditional approach in the wind industry: top-down fidelity. From high fidelity to engineering models to allow reasonable calculation time. Accurate structural design needs to capture enough design situations.



• Relevant models for design certification are checked against prototype measurements

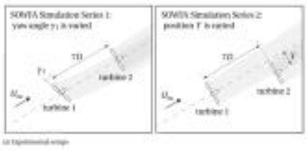
• Alternatives:
Virtual Prototyping. Model tests.

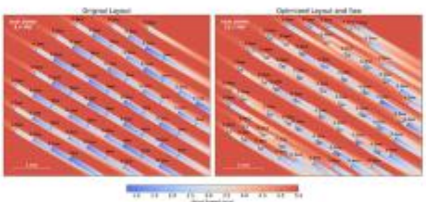
SIEMENS Gamesa RENEWABLE ENERGY

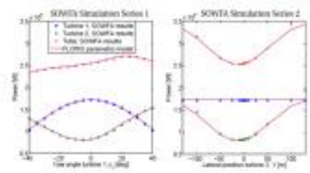
Siemens Gamesa Renewable Energy – Wake Steering as HFM

• Traditional approach in the wind industry: extensive use of Fransen & Jensen models.

• Higher fidelity models were required: more complex aerodynamics for operation at high yaw misalignment (CFD and parametric models)







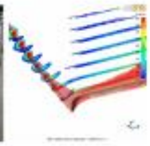
• Setup and results for the SOWFA Simulation (CFD HFM) against FLORIS model (parametric model for wake effects which has limited number of parameters that are estimated based on turbine electrical power production data)

SIEMENS Gamesa RENEWABLE ENERGY

Siemens Gamesa Renewable Energy – Siemens Gamesa full of HFM but also LFM

- HFM: Advanced CFD model for aerodynamic and aeroacoustic design. Enhancing hydrodynamic models with international JIP: WiFi. Structural Superelements to represent foundations / nacelle components.

- LFM: Mainly used in conceptual design, of a new product or a new features. HFM are used to tune LFM, less CPU demanded.



SIEMENS Gamesa RENEWABLE ENERGY

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INTRODUCTION

Tecnalia Research & Innovation: Offshore Renewable Energy area

NAUTILUS Floating Solutions S.L.

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Introduction \ **Offshore Renewable Energy area**

- **20 people** devoted to the development of technology for the offshore renewable sector **since 2004**, totaling more than €30m worth of R&D.
- Part of Energy and Environment Division -220 people-
- Three main **research lines**: wave energy, offshore wind, grid integration of offshore renewables.
- **Two spin-offs** –OCEANTEC and NAUTILUS- and **4 patents** for the connection of offshore energy technologies.
- Experience in **open-sea testing** of wave energy devices.
- Active participation in the main projects, committees, and standardization groups for the development of marine energy and floating offshore wind.
- Organization of international and national events, including ICOE (the International Conference on Ocean Energy) in 2010.

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Introduction \ **NAUTILUS Floating Solutions S.L.**

nautilus floating solutions

tecnalia Inspiring Business

ASTILLEROS DE MURUETA

VICINAY CADENAS, S.A.

TAMOIN

velatia

Acuerdo de colaboración

IBERDROLA

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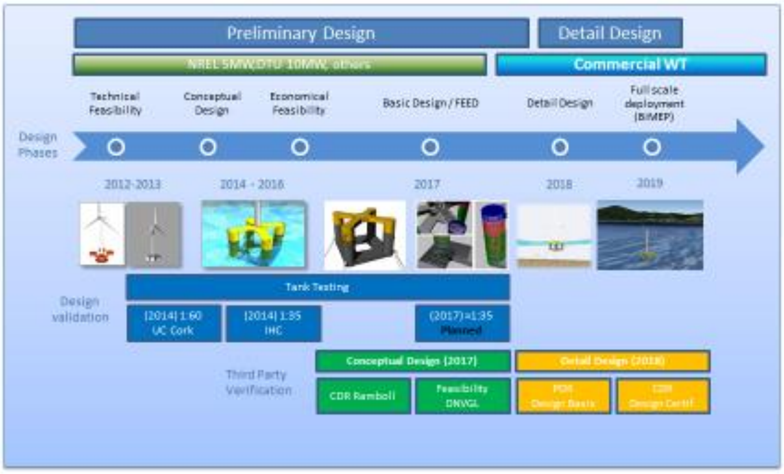
Introduction \ **NAUTILUS Floating Solutions S.L.**



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Introduction \ **NAUTILUS Floating Solutions S.L.**

LIFES50+ Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m.

Basic design and certification DLCs for:

- **DTU 10 MW RNA** and controller
- **3 different sites**: Bay of Maine, Golfe de Fos and West of Barra.

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Introduction \ **NAUTILUS Floating Solutions S.L.**

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NAUTILUS SEMISUBMERSIBLE

Concept

Precedent experimental tests campaigns

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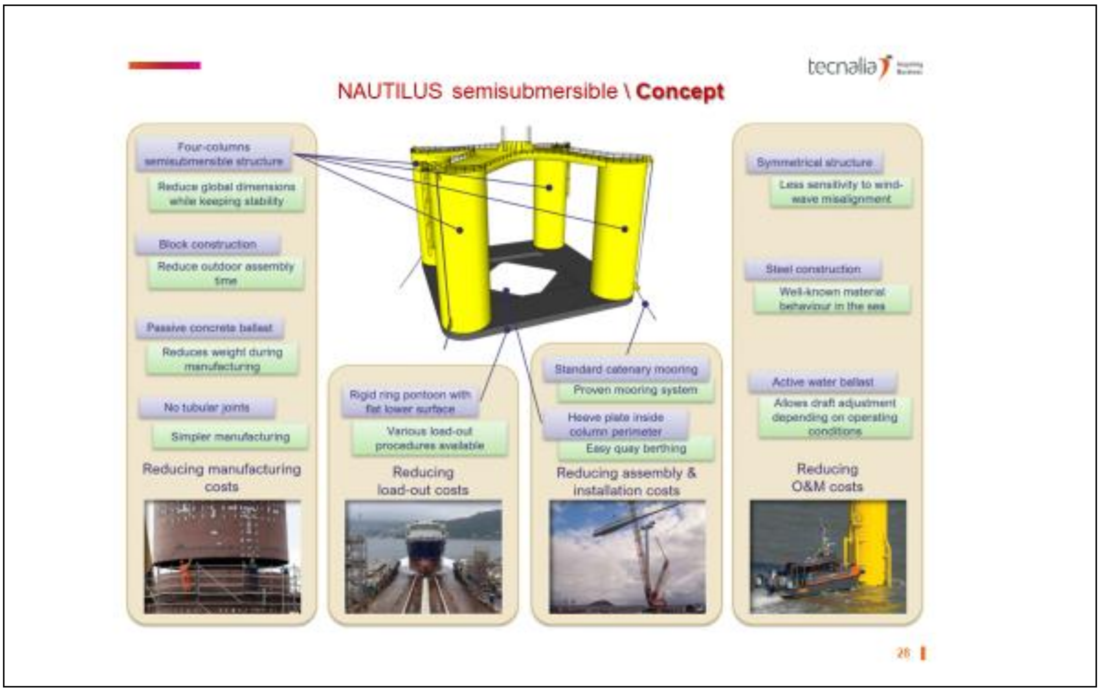

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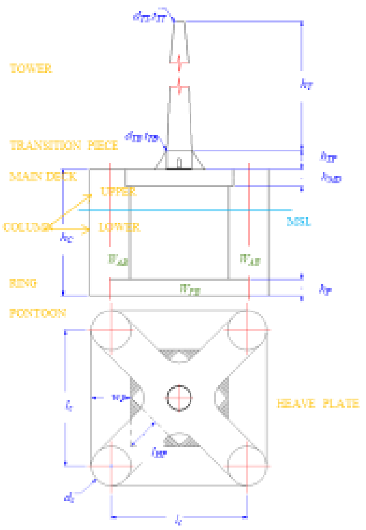
NAUTILUS semisubmersible \ **Concept**



Sketch of NAUTILUS semisubmersible.

Site: BiMEP ($H_{s,50y}$~ 15 m)

Wind Turbine: NREL 5 MW

- **Permanent** (passive) **ballast** inside ring pontoon.
- NAUTILUS platform **trim system** (active) ballast inside columns.
- Central heave-plate.

NAUTILUS main dimensions		
Column diameter, d_c	**9.5**	m
Column distance, L_c	**33**	m
Depth, h_c	**30**	m
Operational draft	19.8	m
Transit draft	5.75	m
Hub height above MSL	89	m
Displacement	~7,000	Ton

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NAUTILUS semisubmersible \ **Precedent experimental tests campaigns**

-	DESCRIPTION	HRMC 1/60	IHC 1/35
EXPERIMENTAL TESTS	Static offset	YES	YES
	Towing	NO	YES
	Decay • Free floating • Moored	 YES YES	 YES YES
	Forced oscillations	NO	NO
	Waves only • Regular • Irregular	 YES YES	 YES YES
	Waves & Wind* • Regular & Unirform • Irregular and Uniform	* Hanging weight YES YES	*Rotor disk YES YES
	Waves, Wind & Current	NO	YES
SENSORS	Floater motion Nacelle acceleration Wind thurst Mooring line tension	YES	YES
	Pressure on the hull	NO	NO

2014 NREL 5 MW on Nautilus during wave & wind test at HMRC (left).

2014 NREL 5 MW on NAUTILUS during wave and wind test at IHC (bottom)

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EXPERIMENTAL TESTS AT Ifremer

Ifremer: Institut français de recherche pour l'explotation de la mer

Experimental model and tests planned

Numerical simulation of tests

Ifremer MaRINET2

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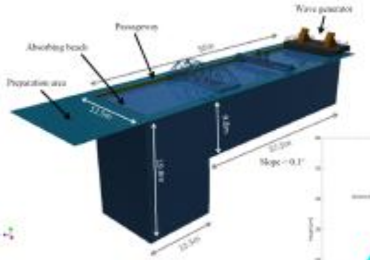
Experimental tests at Ifremer \ **Ifremer (Brest, France)**

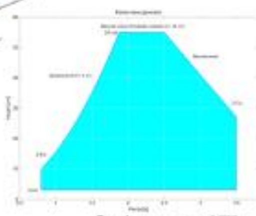
Institut français de recherche pour l'explotation de la mer located in Brest, France.

Their main equipment includes:

- Tank test
- Wave generator
- Hexapod
- Wind generators



Wave tank dimensions. (Source: Ifremer)



Regular waves capabilities (Source: Ifremer)

View of the hexapod configured for forced oscillations tests (Source: Ifremer)

Degrés de liberté	Courses	Vitesses	Accélérations
Mouvement linéaire TX / Surge	± 400 mm	± 1000 mm/s	± 10 m/s²
Mouvement linéaire TY / Sway	± 400 mm	± 1000 mm/s	± 10 m/s²
Mouvement linéaire TZ / Heave	± 400 mm	± 850 mm/s	± 8 m/s²
Mouvement angulaire RX / Roll	± 30 °	± 50 °/s	± 500 °/s²
Mouvement angulaire RY / Pitch	± 30 °	± 50 °/s	± 500 °/s²
Mouvement angulaire RZ / Yaw	± 40 °	± 70 °/s	± 780 °/s²

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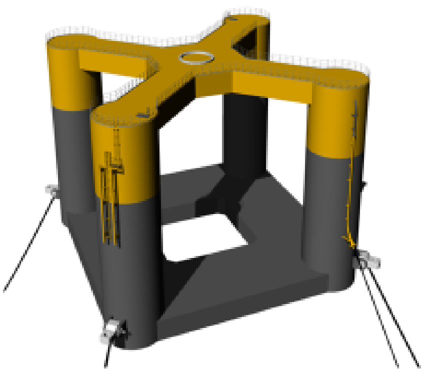
Experimental tests at Ifremer \ **Experimental model and tests planned**

Objectives: **Full hydrodynamic characterisation** of the FOWT. Reduced uncertainty experiments: No aerodynamics nor control dynamics. Controlled mooring stiffness.

When: Begining of 2018 (**10 days**)

Experimental model:

- Scale: To be defined.
- No interior heave-plates (wider pontoon).
- Wind Turbine (RNA + Tower) mass and inertia considered, but not physical representation.
- No catenary mooring (aerial mooring with constant sitffness).



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Experimental tests at Ifremer \ **Experimental model and tests planned**

·	DESCRIPTION	Ifremer 1/¿?	Tests definition
EXPERIMENTAL TESTS	Static offset	YES	-
	Towing	NO	-
	Decay • Free floating • Moored	 YES YES	2 amplitudes 3 repetitions
	Forced oscillations	YES	4 DOFs 2 amplitudes 3 frequencies 2 repetitions
	Waves only • Regular • Irregular	 YES YES	1 repetition (2 wave H_S, 5 wave T_P) (White noise, Jonswap 2 wave H_S)
	Waves & Wind • Regular & Unirform • Irregular and Uniform	 NO NO	-
	Waves, Wind & Current	NO	-

·	DESCRIPTION	Ifremer 1/¿?
SENSORS	Wave elevation Floater motion (Qualisys) Mooring line tension	YES
	Pressure on the hull	¿?

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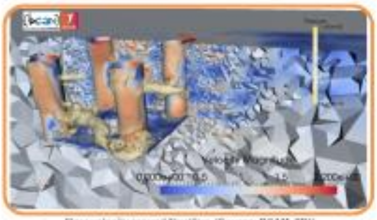
Experimental tests at Ifremer \ **Numerical simulations of tests**

- One of the most important outcome from tank tests is the information that permits the **identification of the system's properties**.
- Experimental measurements make possible the **calibration and validation of numerical models**.
- Tank tests results postprocessing is a time-consuming signal processing task.

TECNALIA will employ engineeriering and CFD models to simulate the experimental hydrodynamics of the tests.

Engineering level codes:
- HydroDyn
- OrcaFlex

CFD codes:
- OpenFOAM
- DualSPHysics coupled with MoorDyn



Flow velocity around Nautilus. (Source: BCAM, TRI)

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OPEN DISCUSSION

Conclusions

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Open discussion \ **Conclusions**

- **Hydrodynamics study!**
- **Uncertainty reduction**: aerial mooring, several repetitions per test, direct and indirect postprocessing techniques.
- **Hydrodynamic nonlinearities analysis**: different initial conditions for decay tests; forced oscillations considerring different frequencies and amplitudes and wave tests considering different waves (H_S, T_P).

Possible validation case for future OC6 project???

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Improving a BEM Yaw Model Based on NewMexico Experimental Data and Vortex/CFD Simulations

F. Blondel

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1 et 4 Avenue du Bois Préau,
92500 Rueil-Malmaison.

IEA Task 11 - Topical expert meeting

DeepLines Wind^{TM}: a design tool

FOWTs prototypes :

- French call for projects
- 3 x 8MW (Siemens), 2020
- Fos Sur Mer, Méditerranée

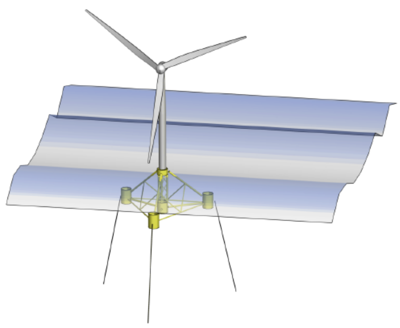
Principia / IFPEN co-developpement

- Finite elements solver
- Hydro- and Aerodynamics
- Wind and wave models
- Anchor, mooring, controllers...

AeroDeeP: the aerodynamic library

- HAWTs and VAWTs
- BEM (Blade Element Momentum)

DeepLines Wind™
Offshore Wind Turbines FEA Software

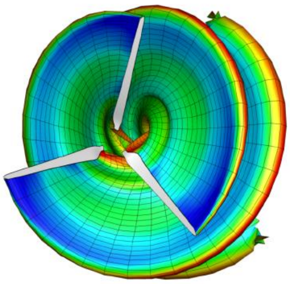


Alternatives to the BEM

BEM: empirical method → Needs validation / calibration
Code to code **and** code to measurements comparisons

Vortex methods

- CASTOR (solver IFPEN)
- Lifting-line method
- Free wake (filaments)
- Dynamic stall
- HAWTs et VAWTs (2D and 3D)
- *GPU* parallelisation (CUDA)



Advantages

- Wake is computed
- Lagrangien → low diffusion
- Simulation setup is very easy

Drawbacks

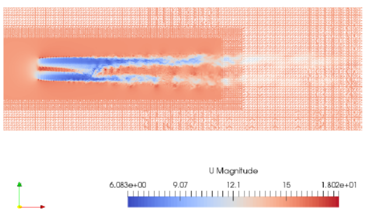
- Inviscid flow model
- Simulation cost : ≈ affordable
- Empirical fix (tower, stall, 3D)

Alternatives to the BEM

BEM: empirical method → Needs validation / calibration
Code to code **and** code to measurements comparisons

CFD + Actuator-Line

- Lifting-line model
- Immersed within a CFD flow field
- SOWFA (NREL): based on OpenFoam
- Multi-levels, cartesian meshes
- 24 million cells, $24D \times 6D \times 6D$
- Large Eddy simulation



Advantages

- Viscous flow model
- Flexible model (ABL, complex terrain...)

Drawbacks

- Difficult to set-up
- High CPU cost

Test case: Mexico wind turbine

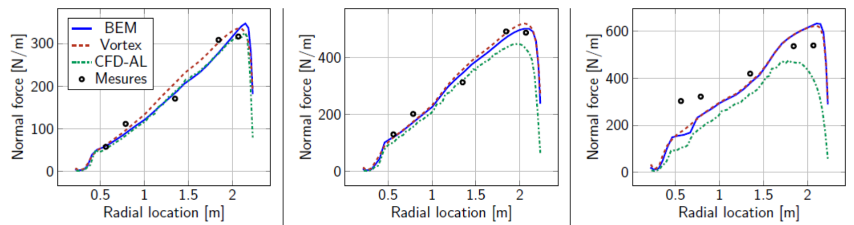
Wind turbine:

- MextNext project (IEA Wind)
- 3-bladed turbine, $\mathcal{R}e \approx 0.5M$
- Large database (winds, yaw, inflow, pitch, omega)
- Rated wind: $15m/s$

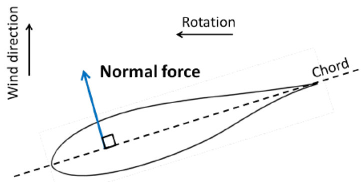
Measured data:

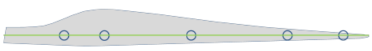
- Pressure sensors at 5 radial locations
- PIV measurements in the near wake
- Acoustic measuremetns

Axial inflow: blade loads

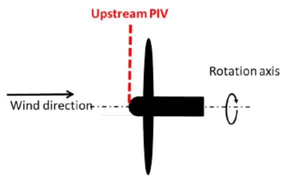


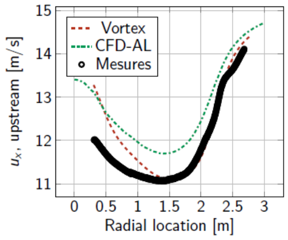
(a) $U_\infty = 10m/s$ (b) $U_\infty = 15m/s$ (c) $U_\infty = 24m/s$

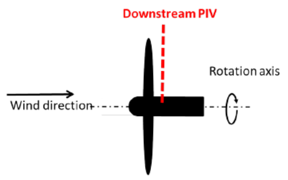


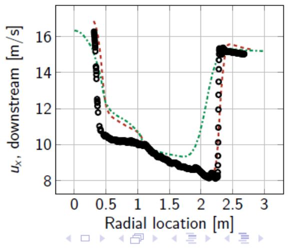


Axial inflow: PIV measurements, $U_\infty = 15m/s$ - Average - $[\pm 0.03m, 0, 0 \rightarrow 1.2R]$









Axial inflow: conclusions

Blade loads:

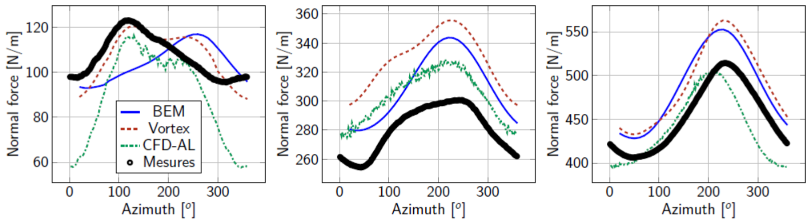
- Accurate predictions for the BEM
- Discrepancies near the blade tip
- Discrepancies at low wind velocities (Turbulent Wake State)
- CFD slightly under-estimate the loads, especially at high wind velocity

Velocities in the wake:

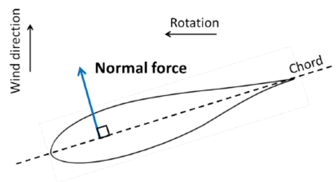
- Vortex solver seems very accurate
- Discrepencies near the root due to the absence of hub
- CFM seems to be less "sharp" $\rightarrow$ high diffusion

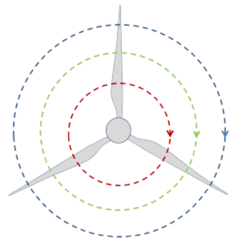
$\rightarrow$ **A more complex test case: yaw misalignment (30^o)**

Yawed inflow: blade loads



(a) Blade root (b) Mid span (c) Blade tip





Yawed inflow: conclusions

Blade loads:

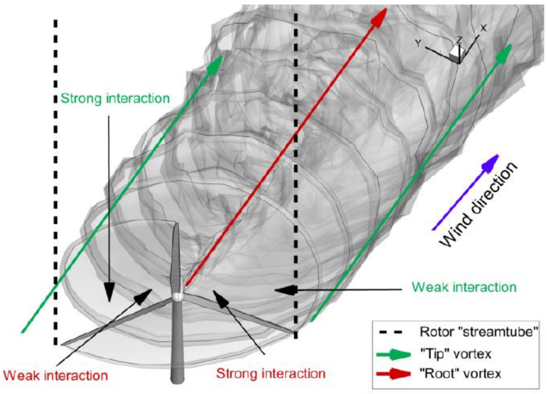
- Unphysical BEM behavior near the root
- $\rightarrow$ badly predicted moment
- Large discrepancies near the blade root (CFD-AL): dynamic stall

Wake velocities:

- See Blondel et al., CFM 2017
- Conclusion are close to the axial inflow ones
- Diffusion is too high with CFD-AL
- Tip vortex is not sharp enough (CFD-AL)

$\rightarrow$ **BEM needs to be further corrected for yaw**

Blade/wake interactions analysis - Vortex method



Blade/wake interactions:

- Distance between blade and vortex → Strong/weak interactions
- Root vortex and tip vortex → opposite interactions
- Advancing/retreating effct → caught by the BEM

Existing models

Glauert yaw model

$$a_{yaw} = a\left[1 + K\frac{r}{R}tan(\chi/2)sin(\psi)\right]$$

- Tip vortex influence
- Sinusoidal evolution (ψ =azimuth)
- Linear increase (r/R)

Schepers model

$$a_{yaw} = a\left[1 - A_1 cos(\phi_r - \psi_1) - A_2 cos(2\phi_r - \psi_2)\right], \quad A_1, A_2, \psi_1, \psi_2 = f(r/R, \chi)$$

- Tip and root vortices
- Evolving phase and amplitude all along the blade
- 20 constants
- Fitting with experimental data required

Loads in yaw - Vortex methods

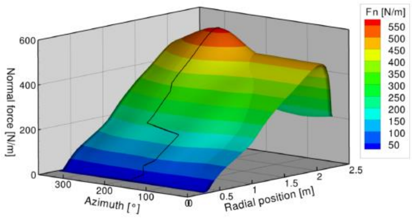


Figure: Normal forces evolution, Yaw=30°

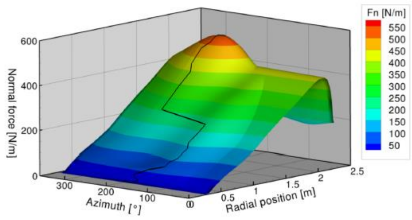


Figure: Normal forces evolution, Yaw=45°

Location of the normal force maxima:

- Only to values under the whole distribution
- Swith values at some blade span
- One value per vortex
- Linear increase/decay of the tip/root vortices influence with span

→ **Observations are not fully consistent with Schepers model**

A simple fix

Tip and root vortices influence, constant phases

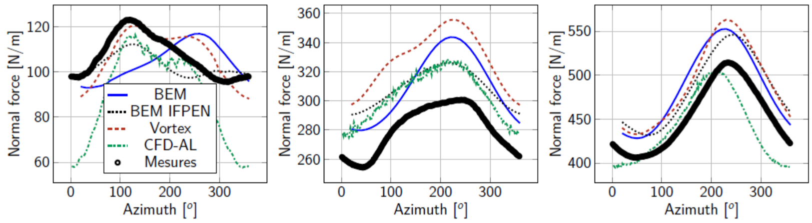
$$a_{yaw} = a[1 + \underbrace{k_1(r/R)\frac{r}{R}tan(\chi/2)sin(\psi+\phi_1)}_{\text{Tip vortex}} + \underbrace{k_2(r/R)\left(1-\frac{r}{R}\right)tan(\chi/2)sin(\psi+\phi_2)}_{\text{Root vortex}}]$$

Linear increase/decay functions and shape parameter

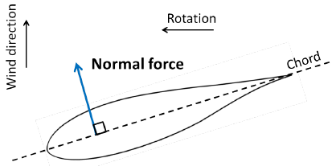
$$k_1(r/R) = (1-A_0) + A_0\frac{r-r_{hub}}{R-r_{hub}} \qquad k_2(r/R) = 1 - A_0\frac{r-r_{hub}}{R-r_{hub}}$$

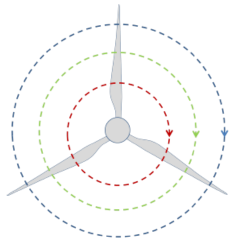
$\phi_1 \approx 0.$ $\phi_2 \approx \pi$ $A_0 = 0.35$

Yawed inflow: blade loads



(a) Blade root (b) Mid-span (c) Blade tip





Conclusions

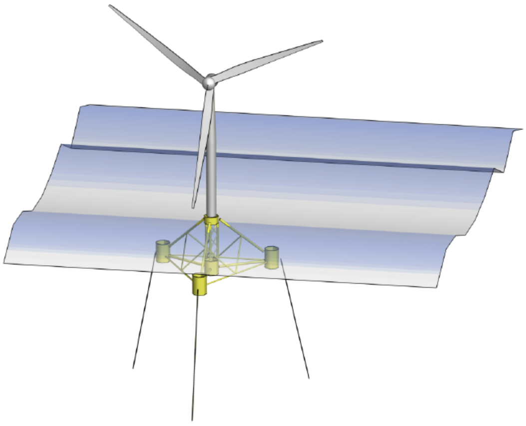
Yaw model:

- Improved behavior
- Validated for several yaw/wind values (cf. Blondel et al., CFM 2017)
- Simple, with few empirical parameters

Methods comparison:

- BEM unavoidable in design phases
- Vortex methods are accurate, but:
  - No hub → discrepancies near the blade root (wake and loads)
  - Computational time too high for design, even using GPUs
  - Inviscid method
- CFD :
  - High diffusion (use higher order schemes, finite elements, LBM)
  - Add stall models

Thanks for your attention



Wind Farm Engineering Modeling and Validation with CFD - Objectives and Methodology

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IEA Task 11 - Topical expert meeting

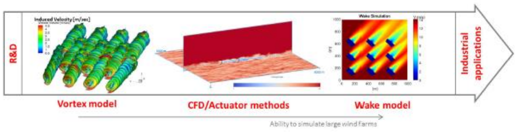
IFPEN developments in wake simulations

Advanced aerodynamic modeling for near wakes

- R&D lifting-line code with free wake (CASTOR) for near wake simulations
- Part of the MexNext project

Early developments in intermediate/far wake and farms modeling

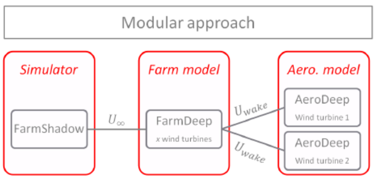
- Engineering wake models with the FarmShadow rigid-body solver
- Coupled CFD / actuator approaches
  - Near and intermediate wake simulations (SOWFA)
  - Mesoscale approach: coupling actuator methods and a meteorological model - PhD thesis, MESO-NH solver (MeteoFrance)



Farm Modelling: Engineering Wake model

FarmShadow: Calculation of blade loads in the farm

- No elasticity
- In-house aerodynamic models
- Wind direction, no roughness



IFPEN focus: identify significant phenomena and increase the physics complexity of the wake modeling in our engineering models

- Influence of the yaw on the wake under steady conditions
- Characterization of the wake under unsteady conditions
  - Due to control strategies of the turbine
  - Due to the motion of the platform in case of floating wind turbines
- Influence of external conditions on the wake
  - Roughness, complex terrains, waves, atmospheric conditions

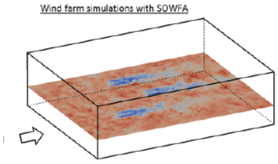
CFD simulation with SOWFA

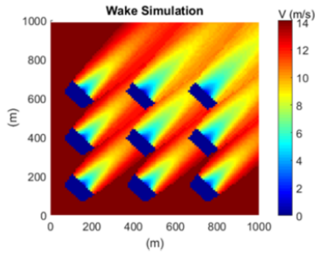
Identify significant phenomena with CFD

- Precursor simulation for atmospheric flow
  - Large periodic domains using LES
- Hybrid simulation for the farm
  - Atmospheric inflow from the precursor
  - LES modeling of the flow inside the domain
  - Actuator line (turbines → body forces)
  - 3 refinements → 30×10^6 cells for 2-3 turbines

Provide data to improve/validate engineering wake models

- Control and optimization of small farms: various configurations (yaw / pitch / position of the turbines / atmospheric conditions...)
- Limited number of CFD simulations (CPU)

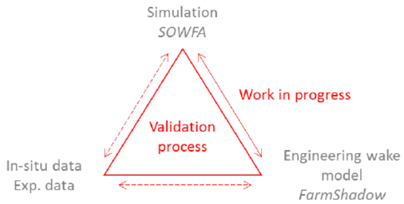




Cathelain, Marie (IFPEN) | Near and far wake modeling: results and future work | IEA Wind | 21 / 23

CFD simulation with SOWFA

IFPEN needs: further comparisons for validation



- Need for field data...
  - Fixed offshore farm
  - Onshore farm, flat terrain
  - Onshore farm, rough terrain
  - Complex terrains
- ... or wind tunnel data

Benchmark with other participants on identified test cases

- IFPEN is part of the MexNext project
- Stronger IFPEN involvement in 2018 based on future simulation results and model developments

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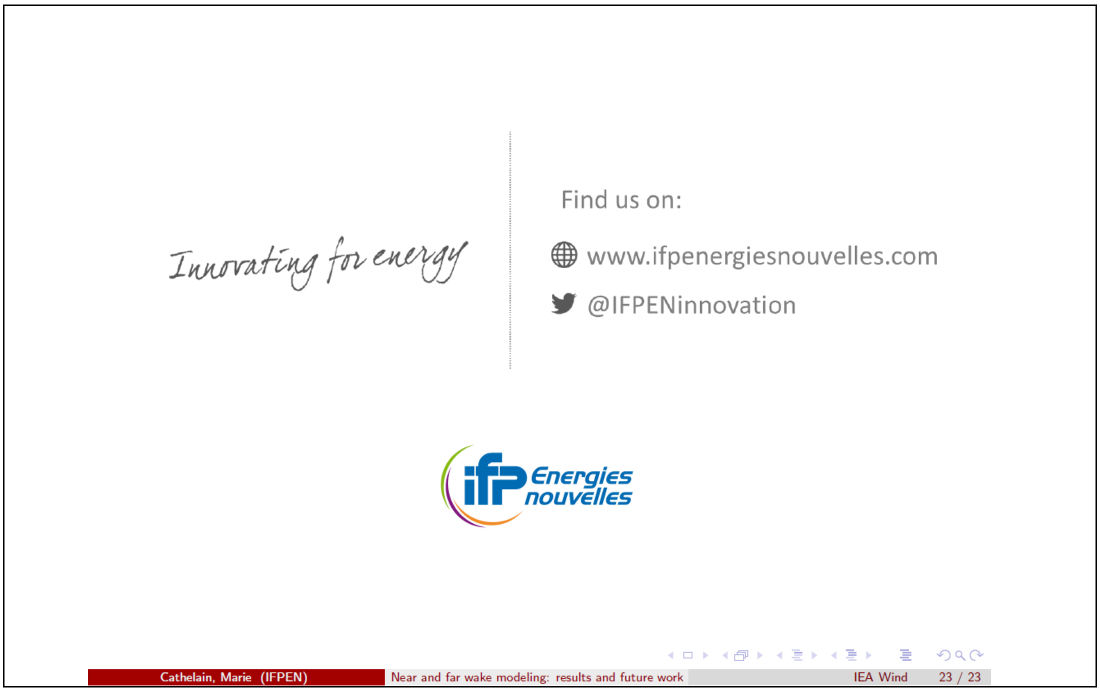
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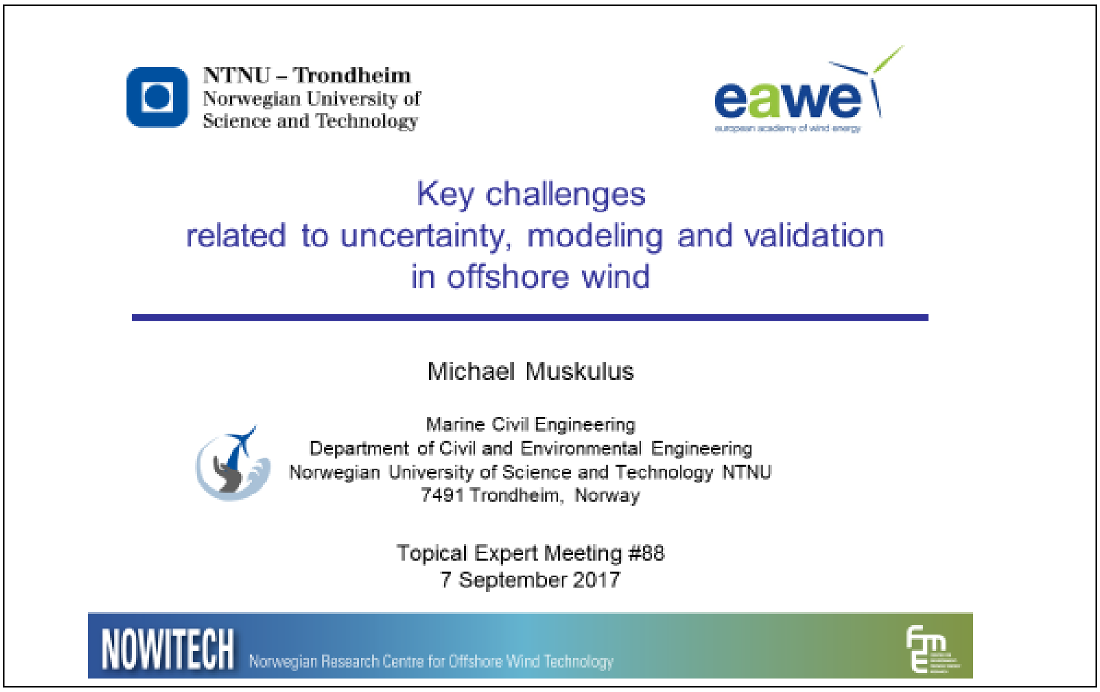
NTNU – Trondheim
Norwegian University of Science and Technology
eawe
european academy of wind energy
Key challenges
related to uncertainty, modeling and validation
in offshore wind
Michael Muskulus
Marine Civil Engineering
Department of Civil and Environmental Engineering
Norwegian University of Science and Technology NTNU
7491 Trondheim, Norway
Topical Expert Meeting #88
7 September 2017
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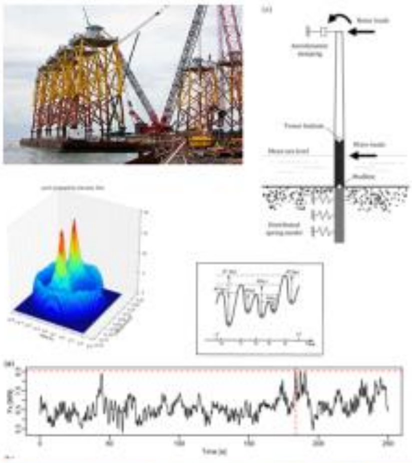
Offshore Wind Turbine Technology Group

Research activities

- **Vibrations** in offshore wind turbine substructures
- **Wave forces** on structures and wind turbines
- **Optimization** of substructure designs including manufacturing aspects and tolerances
- **Alternative designs** including full-height truss tower, downwind turbines, floaters
- **Stochastic dynamics** and system identification
- **Structural reliability** and optimal decision planning
- Condition monitoring and **remaining useful lifetime** estimation



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Current collaborations

AWESOME — Advanced Wind Energy Systems Operation and Maintenance Expertise

ABYSS — Advanced BeYond Shallow waterS – Optimal design of offshore wind turbine support structures

Current applications

ARROWS – Advanced, Reliable and Robust Wind Turbine Structures

STEP4WIND – Training Network in Floating Wind energy

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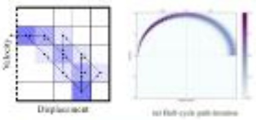
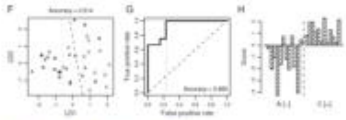
Special interests

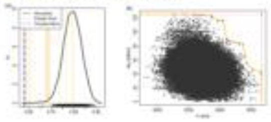
- **Probability evolution methods**



- **Medical diagnostics**



- **Structural reliability**

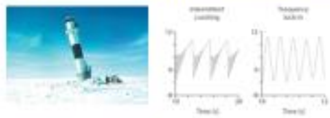


- **Optimal transportation**

$$W(\mu,\nu) = \inf_{\pi \in \Pi(\mu,\nu)} \int_{\Omega\times\Omega} \|x-y\|_2 \, d\pi(x,y)$$

- **High-performance parallel computing**

- **Synchronization and non-smooth dynamics**



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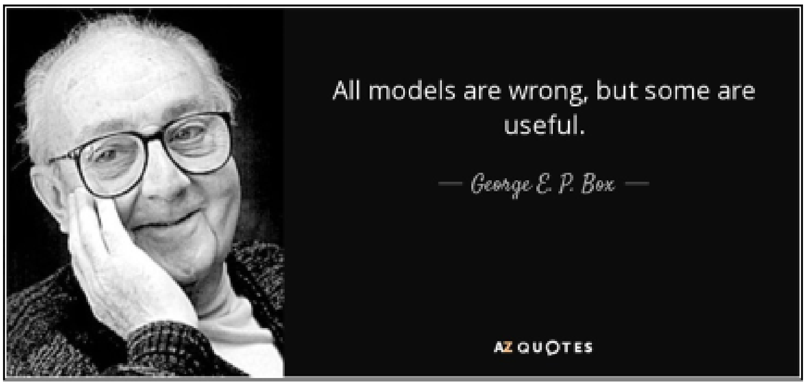

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The engineer's fallacy

«More realistic models are representing reality more accurately, therefore they are better»

But what about:

- Increase in initial conditions, internal states, and model parameters?
- Possibilities for numerical and user error?
- Ease of output analysis (tuning, sensitivity analysis, optimization)?
- Uncertainty quantification?

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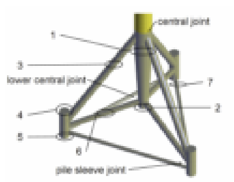
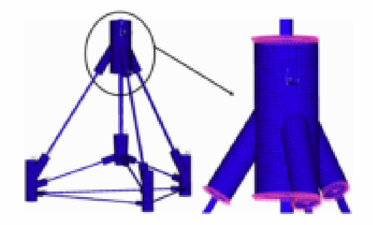
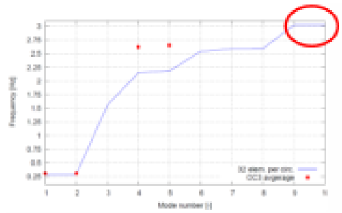
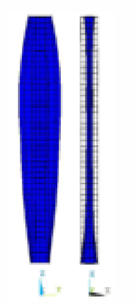
Case in point: Modeling of Alpha Ventus tripod structure









«Frequency differences compared to the results found in the OC3 project can be traced back to the lower fidelity models in this project, and to the complexity of the mode shapes that is not fully representable in those models.»

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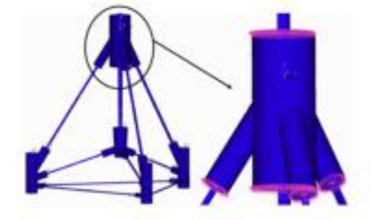
Case in point: Modeling of Alpha Ventus tripod structure

Table 6.4: Axial forces in tripod members.

Sensor	Beam [kN]	Super [kN]
$F_{x,A01}$	-460.9	101.1
$F_{x,A02}$	-262.8	-308.1
$F_{x,A03}$	-5311	-5268
$F_{x,A04}$	-5598	-5549
$F_{x,A05}$	-2461	426.7
$F_{x,A06}$	-613.8	444.2
$F_{x,A07}$	-467.9	422
$F_{x,A08}$	104.6	-1812
$F_{x,A09}$	161.2	29.09
$F_{x,A10}$	106.8	175.1



«The load bearing behavior of the beam- and superelement model ... are totally different. This results from the different stiffnesses of the joints that significantly influence the load path through the structure. The differences due to this effect are surprisingly high.» (Vorpahl 2015)

Validation

Lessons from literature


A Framework for Validation of Computer Models

The key quantity to assess is accuracy of predictions

Tolerance bounds should be given whenever predictions are made

The discrepancy between model and reality is the bias – it should be quantified

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Lessons from literature


A Framework for Validation of Computer Models

x = controllable inputs

u = unknown calibration/tuning parameters

ε = measurement error

$$y^R(x) = y^M(x,u) + b_u(x)$$

$$y^F(x) = y^R(x) + \epsilon^F$$

$$\epsilon^F \sim N\left(0, \frac{1}{\lambda^F}\right)$$

Challenge: If there is bias in the field measurements, there is no data-based way to separate model and field bias

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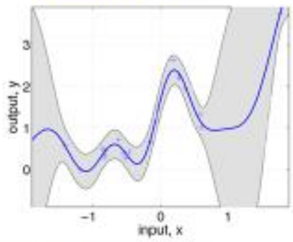
Lessons from literature


A Framework for Validation of Computer Models

Use a Bayesian model

Priors are chosen as follows:

- $p(u)$ is specified, often uniform on a range
- $p(\lambda^F)$ is exponential
- The prior for the bias function will be a Gaussian process



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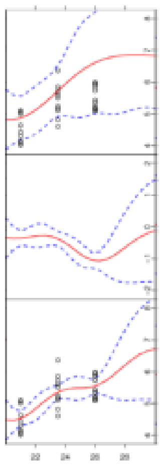
Lessons from literature



MCMC analysis produces a set of N draws i=1,2, …, N from the posterior distribution of the unknowns

$$u^{(i)}, \lambda^{F(i)}, y^M(x, u^{(i)}), b^{(i)}(x)$$

The posterior distribution of all quantitites of interest can be computed from these samples

We can determine the bias function, bias-corrected predictions and tolerance bounds

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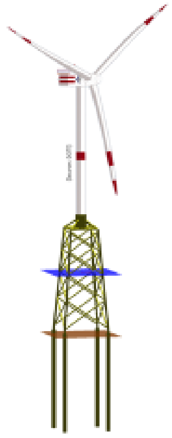
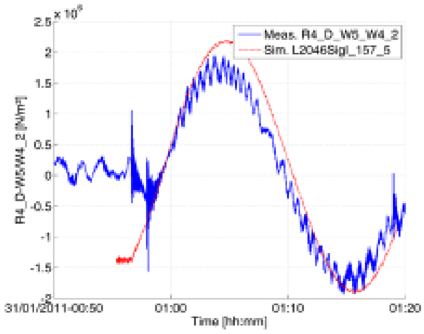
Case in point: Alpha Ventus





Stresses during nacelle rotation

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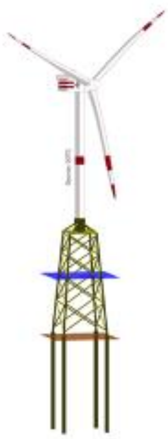
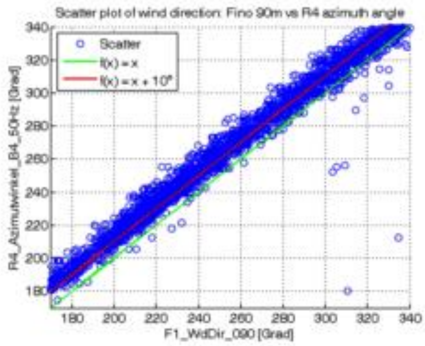
Case in point: Alpha Ventus





Mismatch between measured wind direction
Ad-hoc correction

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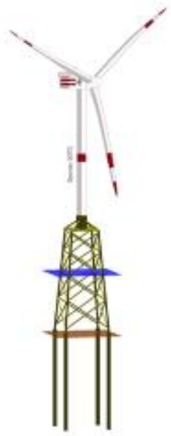
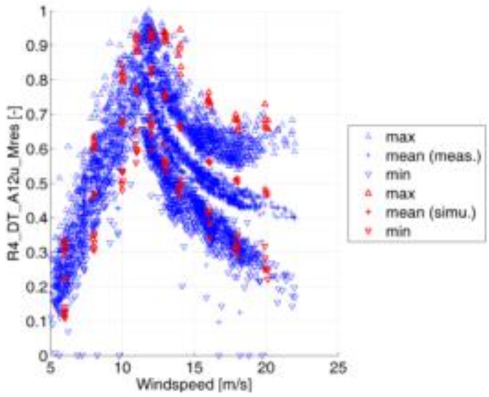
Case in point: Alpha Ventus





Tower bottom bending moment

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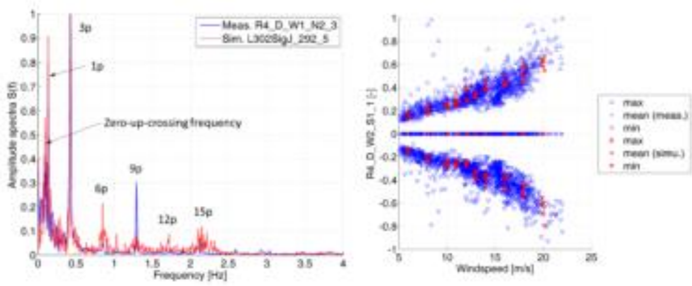
Case in point: Alpha Ventus

«… The results are generally very good, in particular the results of the jacket sensors… Overall, this first load validation is successful…»



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Model updating

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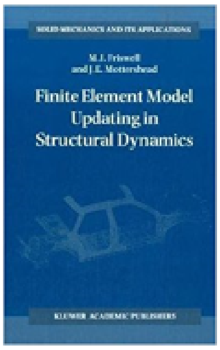
Lessons from literature



Challenge: Mass loading or local stiffness due to attached measurement systems will change the structure

Of course also a lot of purely practical issues with sensors:

- Availability
- Calibration and drift
- Proper identification (channels, coordinate systems)

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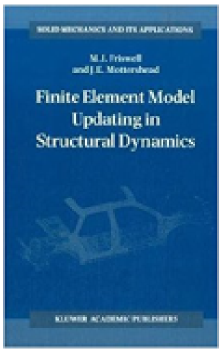
Lessons from literature



Challenge: We need large sensitivity of the model output to tuning parameters

Important difference for representational versus knowledge-based models

«It is impossible to identify a physically meaningful model by system identification» (citing Berman):

- Flexibility matrix K^{-1} can be measured experimentally
- This is dominated by low frequency modes, whereas the stiffness matrix is dominated by high frequency modes

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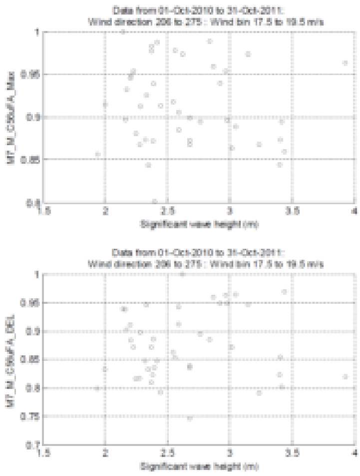
Case in point: Alpha Ventus



«… Initial results from alpha ventus show, however, that the relationship between the statistics of the wave parameters and the loads is not apparent for the sensors at the splash zone…»

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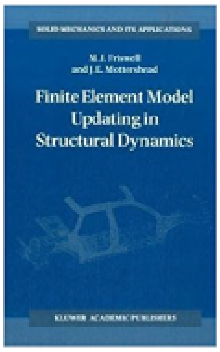
Lessons from literature



Challenge: Selecting transducer locations

Strategy 1: Successive Guyan reduction

- Generate a reduced model that accurately maintains the characteristics of the original model at the lower frequencies
- At slave coordinates the inertia forces are negligible compared to the elastic forces, so choose master coordinates where the inertia is high relative to the stiffness
- The master coordinates of the FE model can also serve as measurement locations for modal testing

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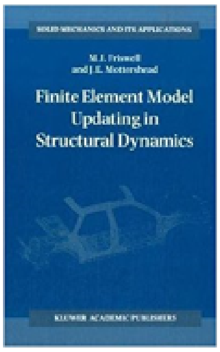
Lessons from literature



Challenge: Selecting transducer locations

Strategy 2: Effective independence

- Select measurement locations which make the mode shapes of interest as linearly independent as possible, while retaining as much information as possible about the selected modal responses in the measurement data
- Uses Fisher information matrix A

$$A = \Phi^t \Phi$$
$$E = \Phi A^{-1} \Phi^t$$

- Terms on the diagonal of E quantify the independence of the chosen modes

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Hydrodynamic loading

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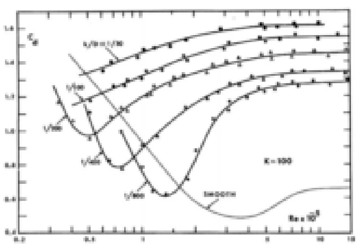
Case in point: Morison equation



«… in spite of the semiempirical nature of Morison's equation, the imperfections of field data, and the vagaries of nature, it has been possible to create monumental engineering structures, with only occasional failures.»

«Numerous attempts have been made either to improve Morison's equation or to devise new equations… So far no satisfactory results have been obtained.»

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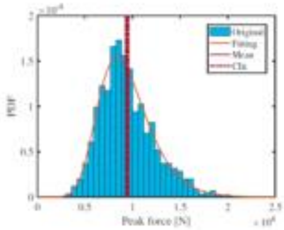
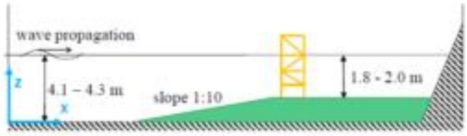
Case in point: Wave breaking (WaveSlam)



This study reveals the uncertainties of the slamming loads under one controlled wave condition in the lab environment.

This part of uncertainties is often neglected in the literature.

(Tu et al., submitted)



Key challenges

1. Field measurements need to be bias-free
2. Sensor locations need to be satisfactory
3. Validation needs clear objectives and criteria
4. Model validation should be quantified in terms of predictive accuracy and tolerance bounds
5. Model updating is only possible if models are sensitive to tuning parameters

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eawe
european academy of wind energy

NTNU – Trondheim
Norwegian University of Science and Technology

The necessary tools exist…

Contact: michael.muskulus@ntnu.no

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Literature

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References

Other works of our group

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- Ziegler L, Smolka U, Cosack N, Muskulus M: **Structural monitoring** for lifetime extension of offshore wind monopiles: Can strain measurements at one level tell us everything? *Wind Energy Science*, under review
- Muskulus M: Pareto-optimal evaluation of **ultimate limit states** in offshore wind turbine structural analysis. *Energies* **8** (2015): 14026-14039

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Coupled dynamics of wind turbines: a multiple-perspective approach

Cristian G. Gebhardt, Clemens Hübler, Karsten Schröder und Raimund Rolfes

Institute of Structural Analysis, Leibniz Universität Hannover

IEA Wind Task 11, Topical Expert Meeting #88,

Edinburgh Training & Conference Venue, Edinburgh

September 7, 2017

7.09.2017

Organization

Part I: Deterministic modeling of wind turbines with DeSiO

- Structural model and aerodynamic loads
- Soil properties and coupled dynamics
- Validations and verifications

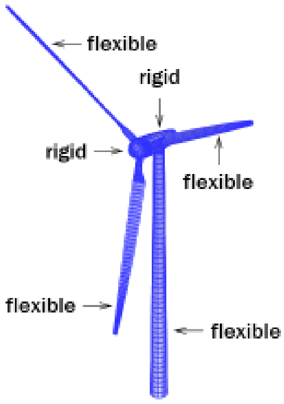
Part II: Probabilistic modeling of wind turbines

- Data basis of scattering environmental conditions
- Sensitivity analysis of offshore wind turbines
- Probabilistic for design and economics

Part III: Hybrid towers for wind turbines - experimental investigations

- Hybrid pre-stressed concrete towers
- Geometry investigated and measurement setup
- Excitation techniques and experiment schedule

Part I: Structural model



Finite element technology:

- Rigid bodies
- Geometrically exact beams
- Solid-degenerate shells

Material:

- Multilayer, general hyperplastic

Multibody systems:

- Rigid/flexible bodies
- Supports/joints

Time-domain Integration:

- MC-EC/ED (robust)

$$\delta S = \int_{t_1}^{t_2} \left\langle \delta \mathbf{s} \cdot \left[\mathbf{l}_z(\mathbf{q}, \mathbf{s}; t) - \mathbf{l}_q(\mathbf{q}; t) \right] + \delta \mathbf{q} \cdot \left[\dot{\mathbf{l}}_z(\mathbf{s}; t) + \mathbf{f}^{int}(\mathbf{q}, \mathbf{s}; t) + \mathbf{H}^T(\mathbf{q}, \xi; t)\boldsymbol{\lambda} - \mathbf{f}^{ext}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}; t, \tau) \right] + \delta \boldsymbol{\lambda} \cdot \mathbf{h}(\mathbf{q}, \xi; t) \right\rangle = \mathbf{0}.$$

Requirements: frame-indifferent, path-independent, at least 2nd-order accurate and robust.

Part I: Aerodynamic loads

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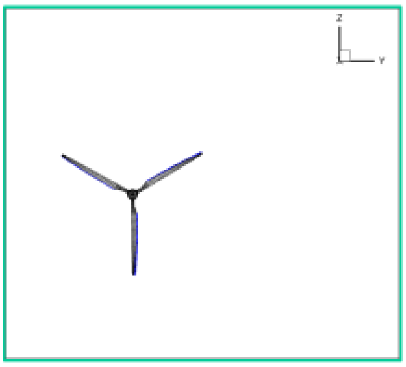
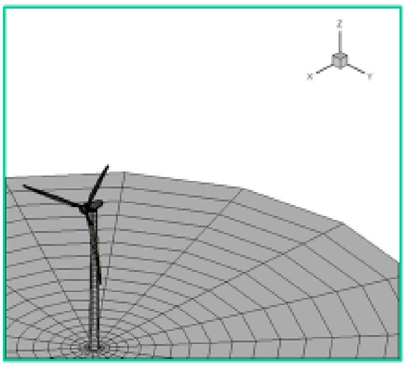
Acting loads on the structure are determined with the boundary-element-method

rotor only, yaw misalignment 30° | all interactions are on





Requirements: unsteady, nonlinear, efficient and robust.

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Part I: Soil properties

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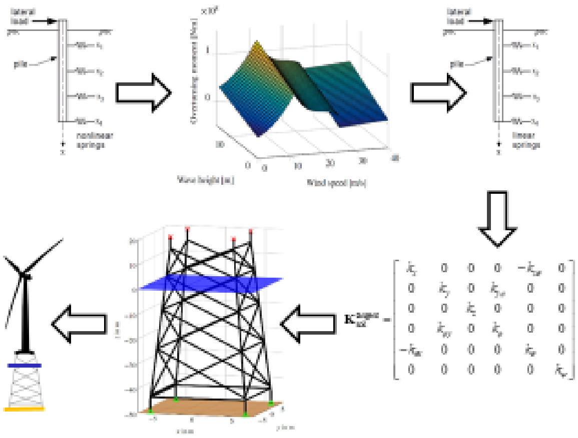
Procedure:

- e.g. Standard nonlinear p-y curves
- Determination of the operating "load" using an response surface
- Linearization at the operating point
- Reduction to a stiffness matrix (no additional DoFs added to the model)
- Inclusion of the stiffness matrices at all base



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Part I: Coupled dynamics

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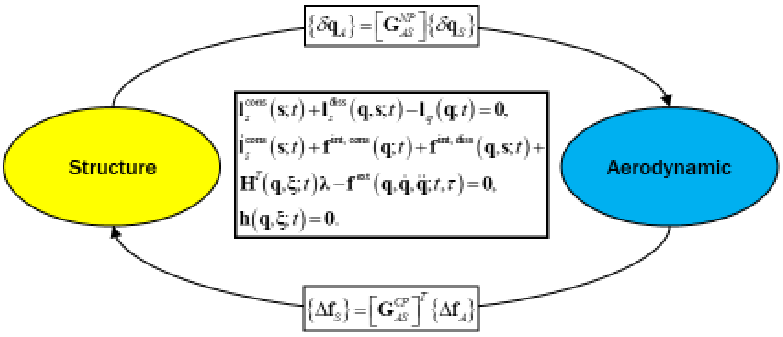
The Question: What does come first in a non-ideal physical problem?



Approach: Two-way strong interaction scheme

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Part I: Validations and verifications

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Passed verification tests:

- All element technology (Abaqus and Ansys)
- Preservation properties, controlled dissipation (Simo and Tarnow, Armero and Romero)
- Flapping wings (Standford and Beran)
- Flutter of a suspension bridge (Fung, Predikman)
- Foundation response (OC3-monopile and OC4-jacket)
- 5MW NREL wind turbine (Jonkman *et al.*)

Passed validation tests:

- Two-blade rotor (Caradona and Tung)
- Flapping wings (Dickinson *et al.*)

Coming validation test:

- DFWind: Two onshore wind turbines completely instrumented: foundation, tower, drivetrain and blades.

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Part II: Data basis of scattering environmental conditions

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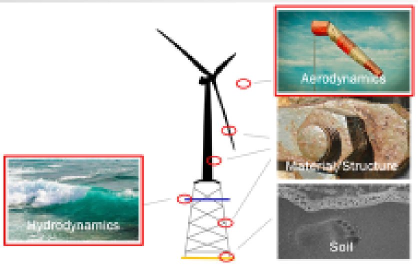
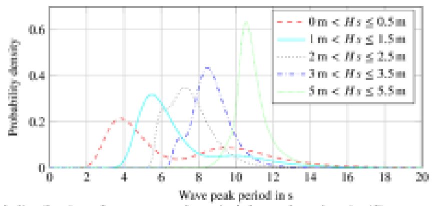
- Environmental conditions are scattering
- Realistic input is scarce
- Creation of an open-access data base for 13 environmental conditions (easy-to-use)
  - wind speed and direction, wave height, direction and period, current speed and direction, turbulence intensity, wind shear etc.
- Based on the high-quality raw data (FINO 1-3)
- Definition of comprehensive and depended statistical distributions





Bi-modal distributions for wave peak period depend on the significant wave hei

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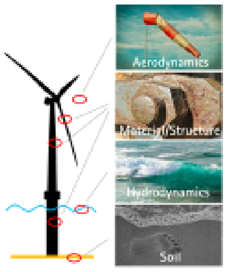
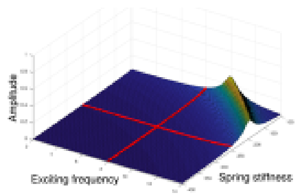
Part II: Sensitivity analysis of offshore wind turbines

ISD INSTITUT FÜR STATIK UND DYNAMIK

- Deterministic simulations are state of the art
- Lifetime distribution and failure probabilities are valuable (probabilistic simulations needed)
- Computing time is high
  ⇒ Reduction of probabilistic subset needed (sensitivity analysis)





Example (spring-mass system) for insufficiently covered interactions using a one-at-a-time analysis (red lines)

Sensitivity analyses:

Parameter studies or one-at-a-time analyses
+ Only a few model evaluations
- No interactions covered

Variance-based approach
- Computational expensive
+ All interactions and higher order effects covered

Stepwise and meta-model based approaches
- Promising compromises between computing time and accuracy

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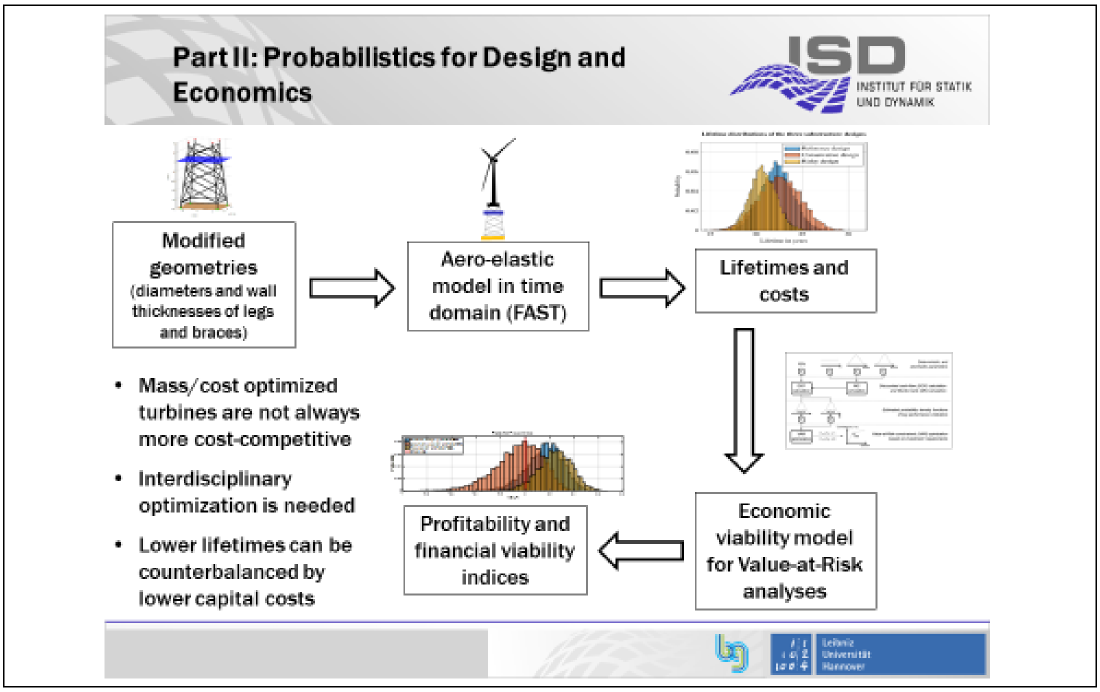
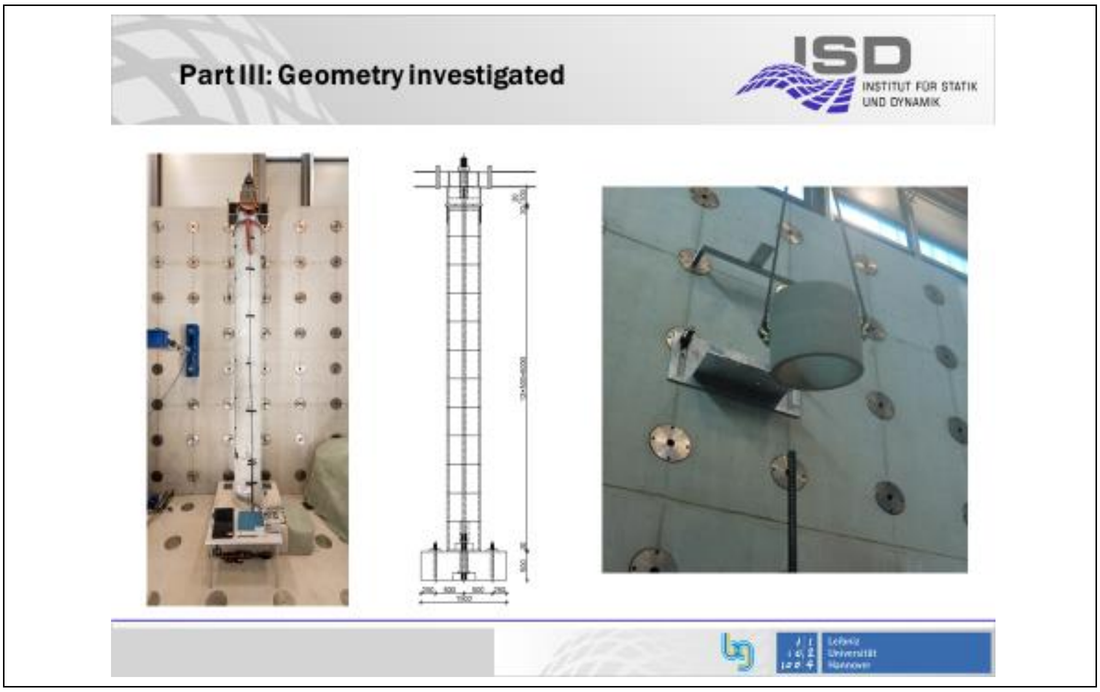

Part II: Probabilistics for Design and Economics
ISD
INSTITUT FÜR STATIK UND DYNAMIK
Modified geometries
(diameters and wall thicknesses of legs and braces)
Aero-elastic model in time domain (FAST)
Lifetimes and costs
Economic viability model for Value-at-Risk analyses
Profitability and financial viability indices
• Mass/cost optimized turbines are not always more cost-competitive
• Interdisciplinary optimization is needed
• Lower lifetimes can be counterbalanced by lower capital costs


Part III: Hybrid pre-stressed concrete towers
ISD
INSTITUT FÜR STATIK UND DYNAMIK


Part III: Geometry investigated
ISD
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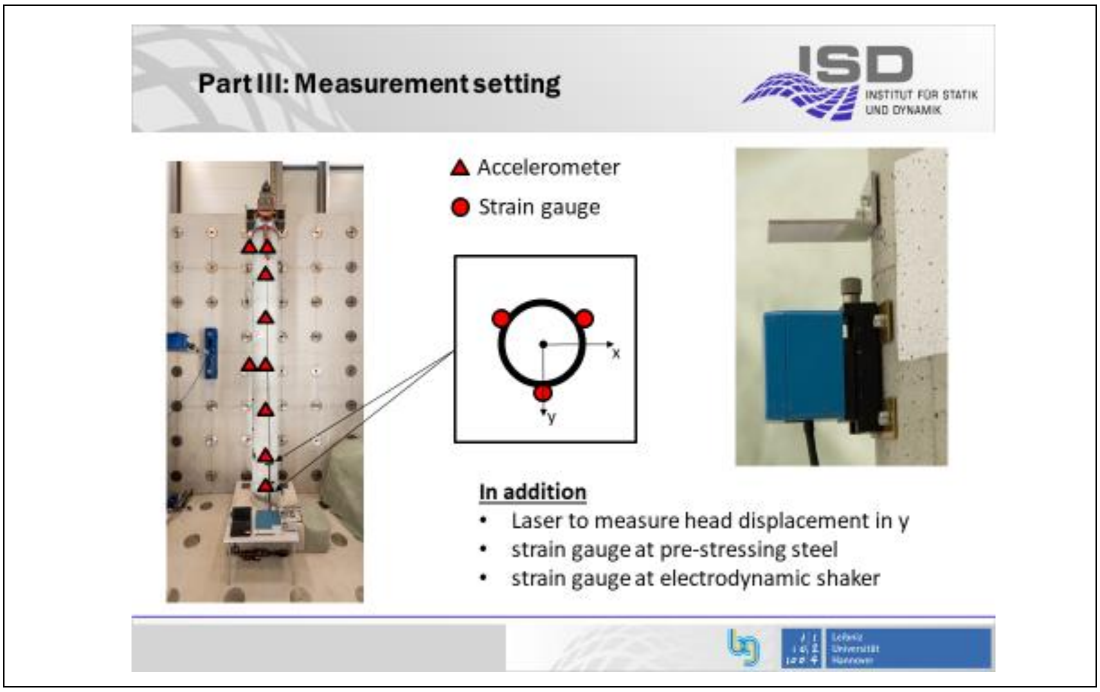
Leibniz Universität Hannover


Part III: Measurement setting
ISD
INSTITUT FÜR STATIK UND DYNAMIK
Accelerometer
Strain gauge
x
y
In addition
• Laser to measure head displacement in y
• strain gauge at pre-stressing steel
• strain gauge at electrodynamic shaker
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Part III: Excitation techniques

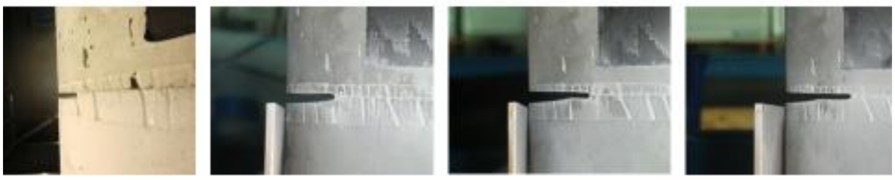
- Hammer impulse 
- Tensile bolts 
- Sweep 

Part III: Experimental schedule

Investigation of

- Undamaged state 23% f_{ck}
- Varying pre-stressing forces (19, 15, 11% f_{ck})
- Undamaged state 20% f_{ck}
- Damage at segment 2 (20-51mm cut, 4 stages)

\+ Determine mechanical properties of concrete, weight of segments...



Conclusions

- Not everything is deterministic, but neither probabilistic
- Advanced methods are still necessary
- Multidisciplinary approaches are necessary
- Combining deterministic models, probabilistic models and experiments
- Validation and verification are concomitant

Thank you very much for you attention!

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Experience with wake model benchmarking in IEA Task 31: Wakebench

Patrick Moriarty

September 7, 2017

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

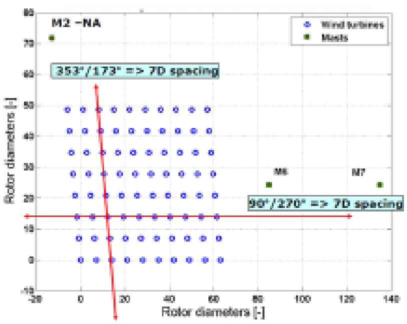
Summary of Wakebench to Date

- Began 2012, Phase II ends 2017
- 14+ Models Benchmarked
- Benchmark Cases
  - Axisymmetric Wake
  - Horns Rev
  - Sexberium
  - Infinite Wind Farm
  - Others without significant participation

Horns Rev – Multiple Wakes

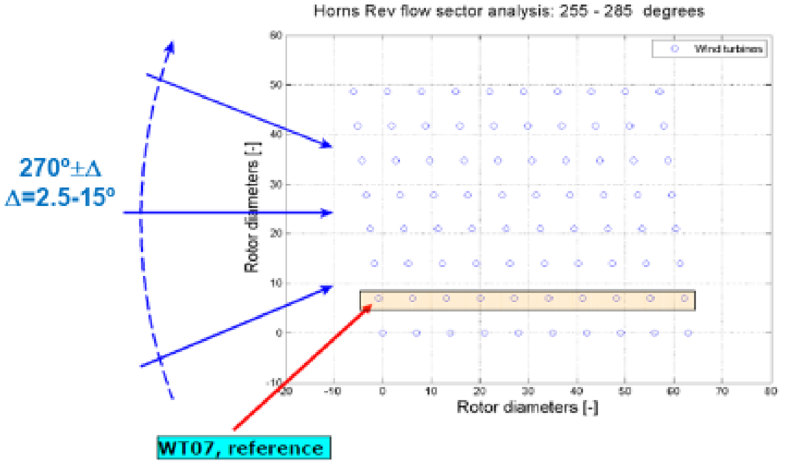
- SCADA data from 80 Vestas V80-2MW, 2005-2007
- Benchmarks:
  - ❑ Neutral, direction sector width: 270º ± {2.5º, 7.5º, 15º}
  - ❑ stability: stable, neutral, unstable
  - ❑ turbulence intensity
  - ❑ turbine spacing: 7D, 9.4D, 10.4D

- In collaboration with the EERA-DTOC EU project



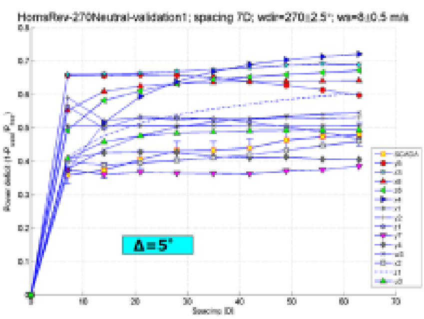
Managed by: Kurt S. Hansen (DTU Wind, Denmark)

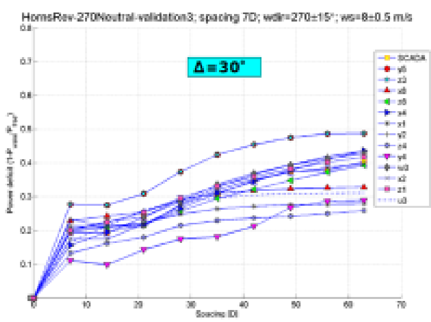
Horns Rev – Wind Sector Sensitivity



Horns Rev – Wind Sector Sensitivity

- Wind sector width creates new benchmarks
- Mesoscale variability
- Large uncertainties in data and models

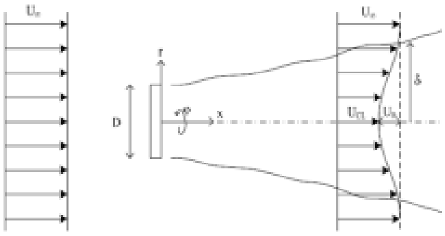


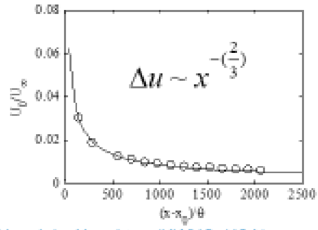


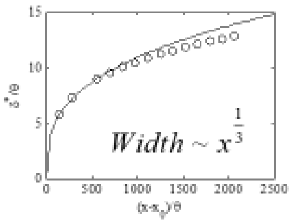
Axisymmetric Wake

Do wake models follow theoretical trends?

- Wake grows as $x^{1/3}$
- Wake deficit decays as $x^{-2/3}$



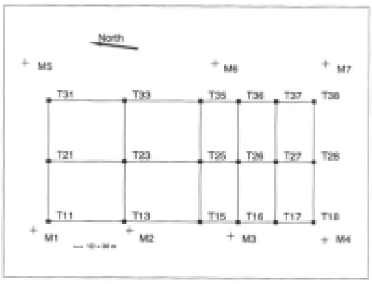




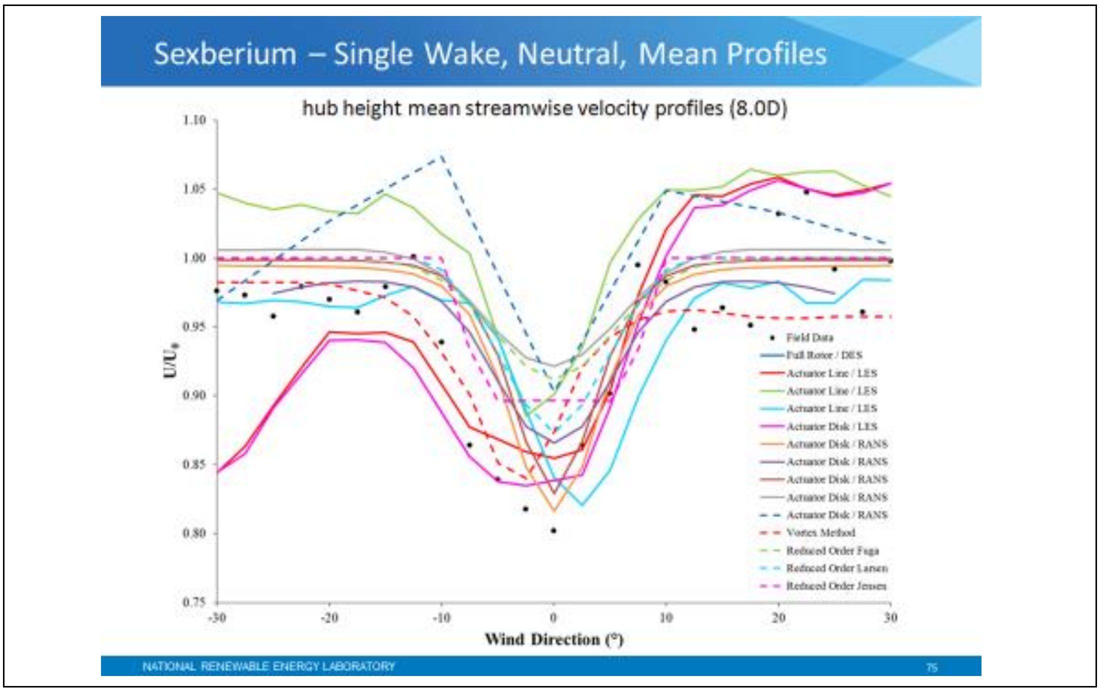
Managed by: John Naughton (UWYO, USA)

Sexberium: Single and Double Wake

- Validation of wake flow field at 2.5D, 5D and 8D behind a HOLEC 310kW 30-m diameter turbine.
- Onshore, flat terrain, neutral conditions, 1992



Managed by: Matt Churchfield (NREL, USA)


Sexberium – Single Wake, Neutral, Mean Profiles
hub height mean streamwise velocity profiles (8.0D)
U/U0
Wind Direction (°)
Field Data
Full Rotor / DES
Actuator Line / LES
Actuator Line / LES
Actuator Line / LES
Actuator Disk / LES
Actuator Disk / RANS
Actuator Disk / RANS
Actuator Disk / RANS
Actuator Disk / RANS
Actuator Disk / RANS
Vortex Method
Reduced Order Fuga
Reduced Order Larsen
Reduced Order Jensen
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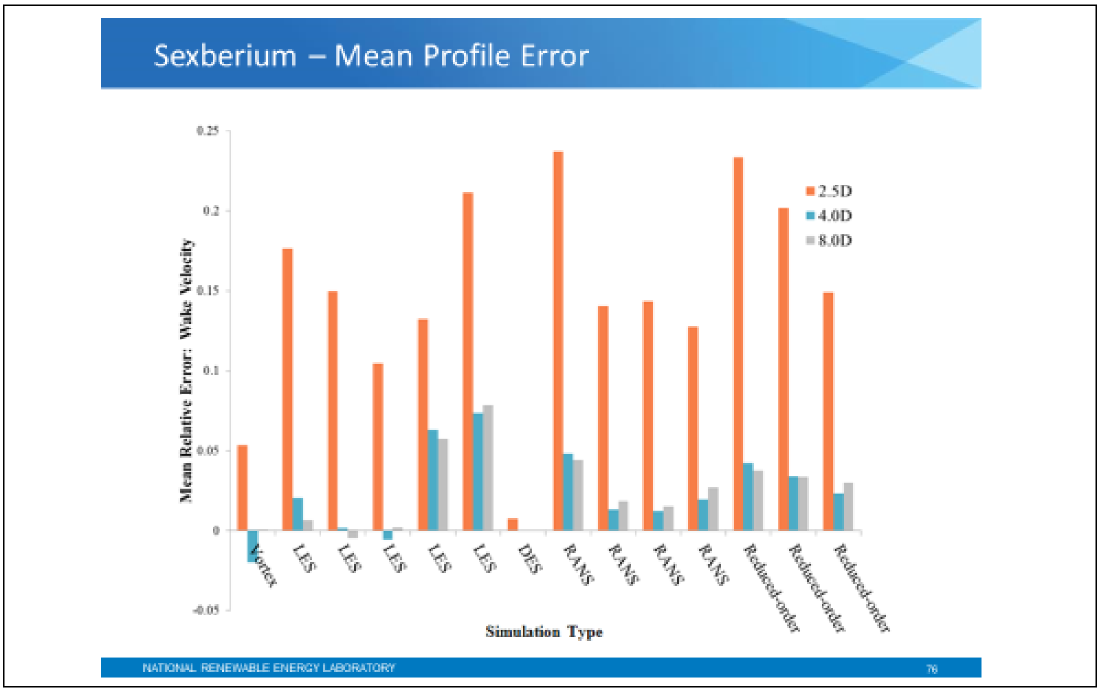
Sexberium – Mean Profile Error
Mean Relative Error: Wake Velocity
Simulation Type
2.5D
4.0D
8.0D
Vortex
LES
LES
LES
LES
LES
DES
RANS
RANS
RANS
RANS
Reduced-order
Reduced-order
Reduced-order
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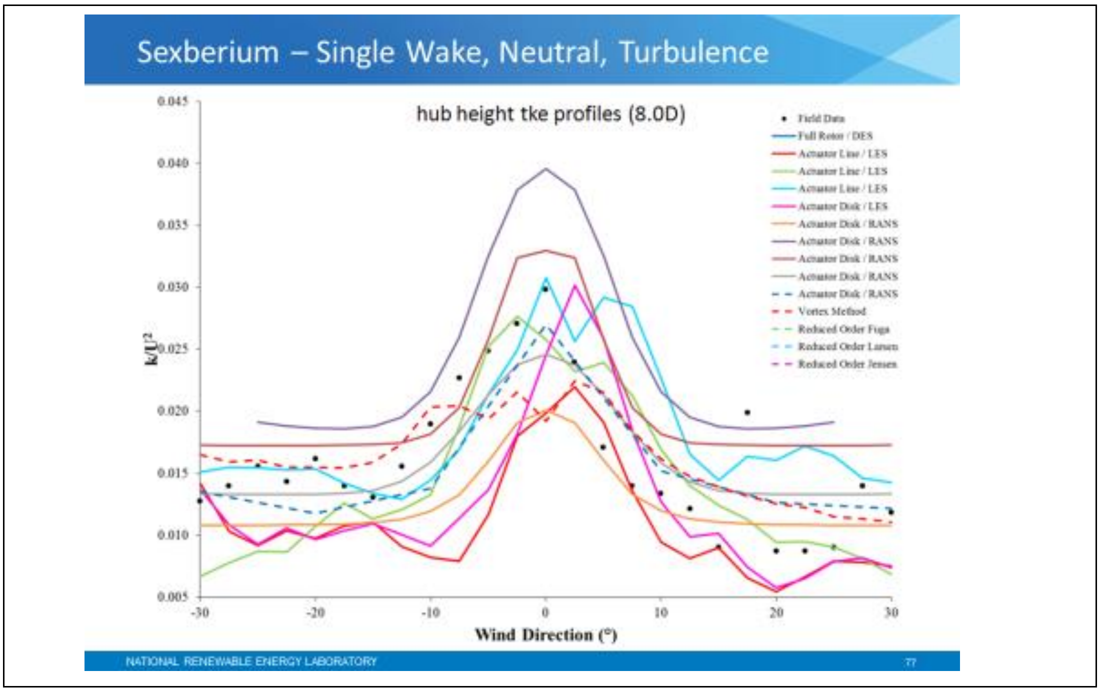

Sexberium – Single Wake, Neutral, Turbulence
hub height tke profiles (8.0D)
Field Data
Full Rotor / DES
Actuator Line / LES
Actuator Line / LES
Actuator Line / LES
Actuator Disk / LES
Actuator Disk / RANS
Actuator Disk / RANS
Actuator Disk / RANS
Actuator Disk / RANS
Actuator Disk / RANS
Vortex Method
Reduced Order Fuga
Reduced Order Larsen
Reduced Order Jensen
k/U²
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
-30
-20
-10
0
10
20
30
Wind Direction (°)
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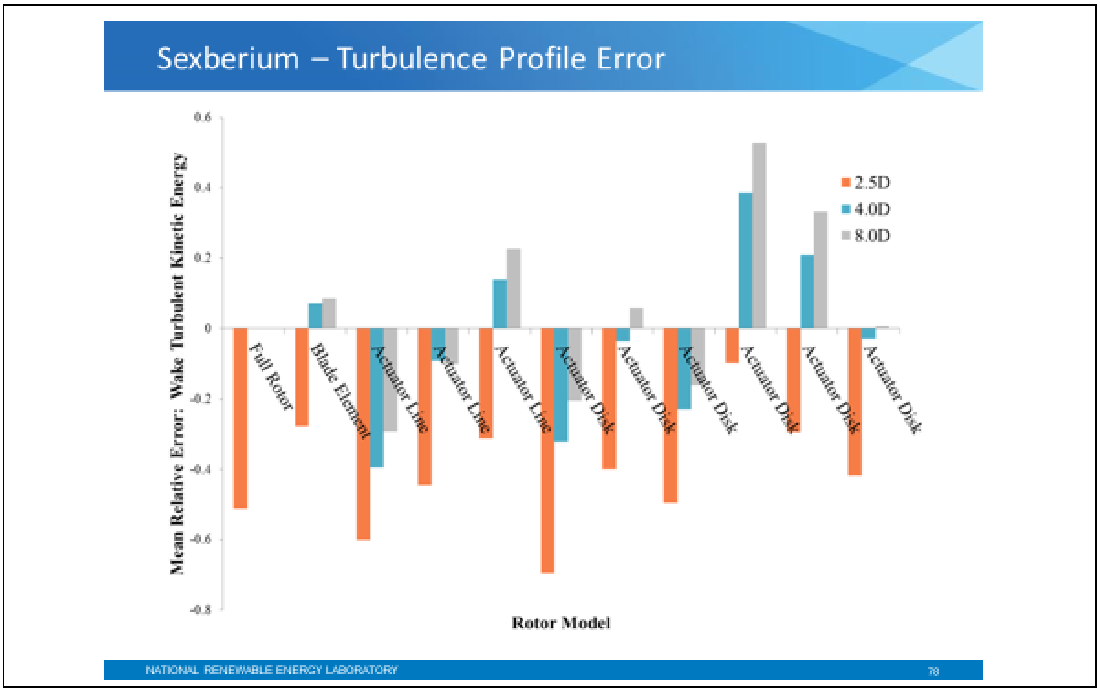

Sexberium – Turbulence Profile Error
Mean Relative Error: Wake Turbulent Kinetic Energy
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
2.5D
4.0D
8.0D
Full Rotor
Blade Element
Actuator Line
Actuator Line
Actuator Line
Actuator Disk
Actuator Disk
Actuator Disk
Actuator Disk
Actuator Disk
Actuator Disk
Rotor Model
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Lessons Learned

- Qualitative comparison, but little additional understanding of what models are better and why
  - Challenging to compare different model types
  - Higher fidelity is often more accurate, but not always
  - User has a big potential impact
  - Best practices linked to model and benchmark
- Benchmark interest variable
  - Closer to reality = more interest = greater uncertainty
  - Fundamental issue of alignment without joint funding
  - Need to demonstrate benefit of validation hierarchy
    - Balance between applied and fundamental benchmarks
- Uncertainty quantification is key

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Forward

- More systematic study of wake models
  - Formal V&V process – ASME V&V process, PIRT tables
  - Demonstrate value of process
- Iterate on one wake benchmark
  - Iterate and track model improvement
  - Fix as many model set up and input variables as possible
    - Remove user variability
    - Grid, inflow, averaging time etc.
    - Difficult across a variety of codes – focus on models that bring additional understanding
  - Improved metrics
  - May lose some participation
- Help design new higher fidelity wake experiments
  - More detailed quantities of interest
- Quantify uncertainty – models and observations
  - What are acceptable levels?
  - What is uncertainty floor (aleatory vs. epistemic)?
  - Demonstrate higher fidelity = lower uncertainty

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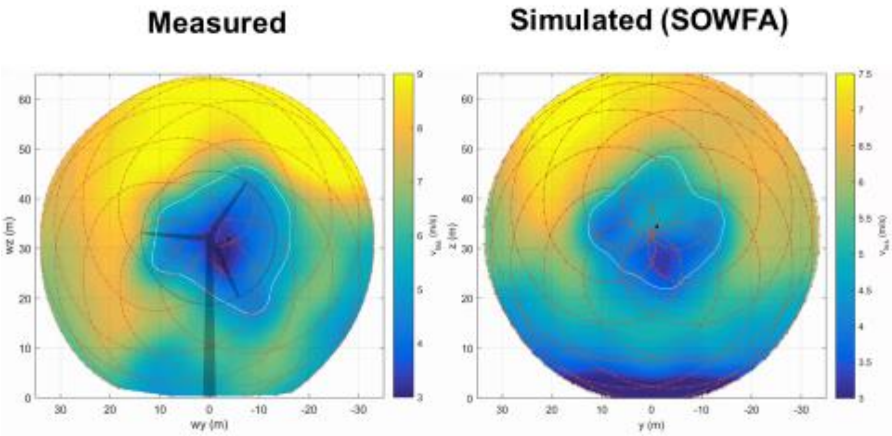
SWiFT Benchmark



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Questions?

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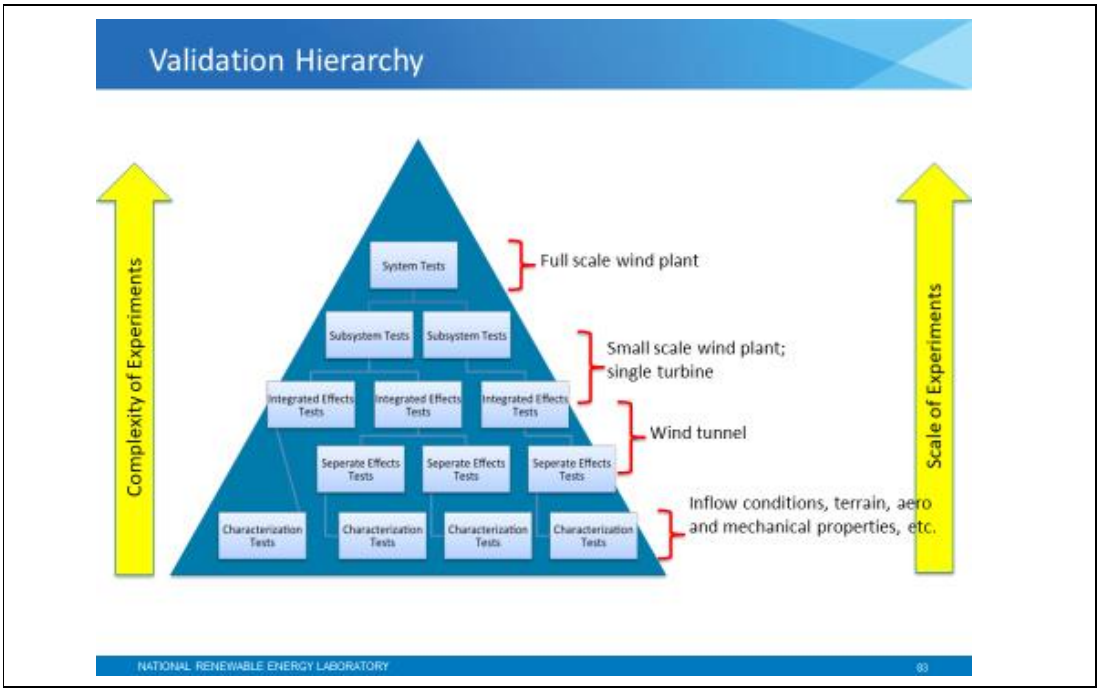
Validation Hierarchy
Complexity of Experiments
System Tests
Subsystem Tests
Subsystem Tests
Integrated Effects Tests
Integrated Effects Tests
Integrated Effects Tests
Seperate Effects Tests
Seperate Effects Tests
Seperate Effects Tests
Characterization Tests
Characterization Tests
Characterization Tests
Characterization Tests
Full scale wind plant
Small scale wind plant; single turbine
Wind tunnel
Inflow conditions, terrain, aero and mechanical properties, etc.
Scale of Experiments
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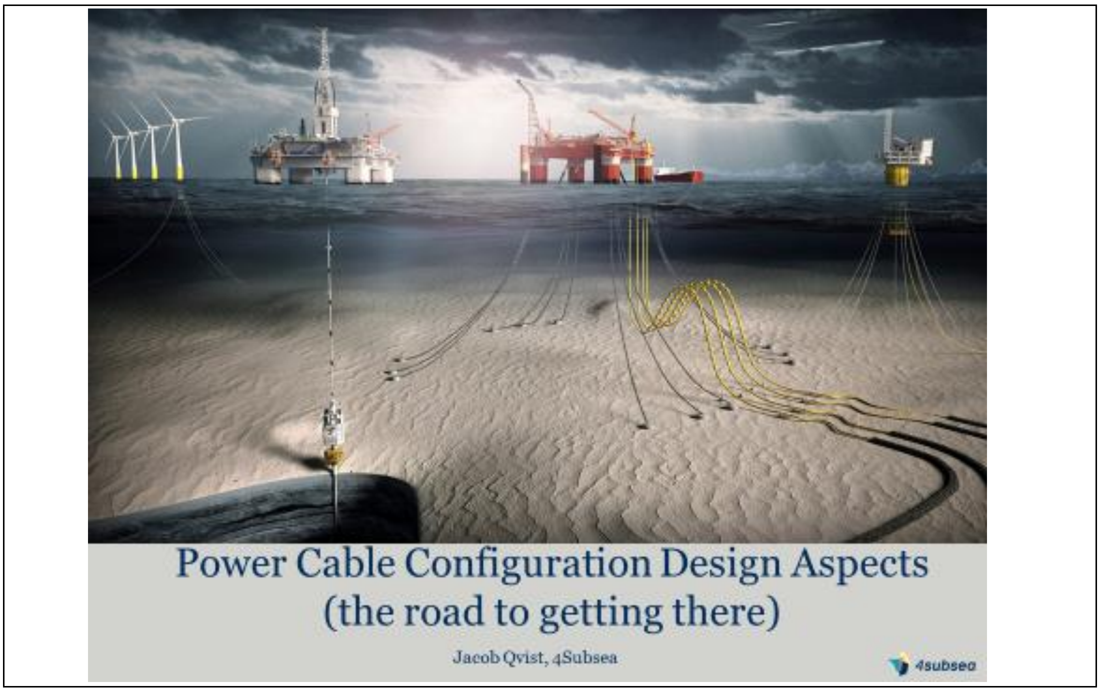
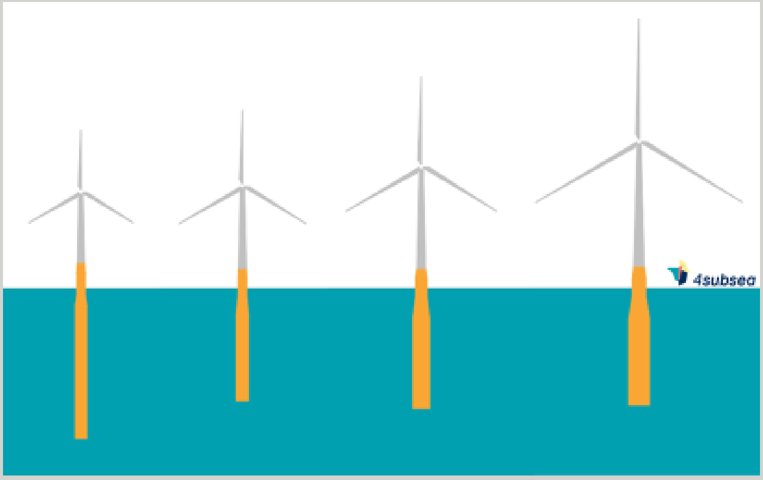

Power Cable Configuration Design Aspects
(the road to getting there)
Jacob Qvist, 4Subsea
4subsea

Hywind Concept Development



Design Considerations

Upscaling: 2.3 MW to 6 MW to ..?

- Design factors
  (dimensions, structural details, SCFs, SN)
- Fabrication
  (codes, welds, materials)
- Ballast
  (type and density)
- Installation
  (tow, upending, assembly, mating)
- Moorings
  (type, layout, dimensions, installation)
- Power cables
  (dimensions, configuration)

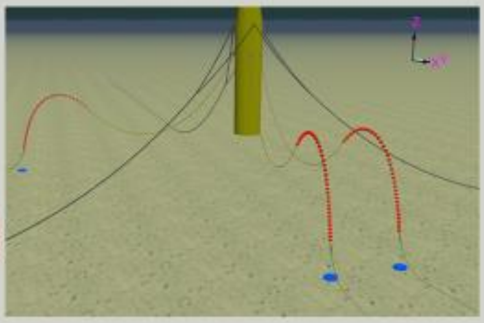
- Site specific conditions
  (Wind, waves, current)
- Park layout
  (headings and routings)
- Uncertainties
  (RNA, controller, tilt)
- Hydrodynamics
  (Morisson, WAMIT, MacCamy Fuchs)

COUPLED ANALYSIS

Power Cable Configuration

Dynamic cable configuration design

- 5 FWTs at different WD
  - 8 x Infield cables
  - 1 x Export cable
- Iterative process
  - ULS
  - FLS
  - ALS
  - Installation
- Ancillary equipment



COUPLED ANALYSIS

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Coupled Analysis

Tool selection

- Level of detail requirements
- Speed! Speed! Speed!
- Availability of rotor / controller
- Substructure flexibility
- Cable EI (non-linear, hysteretic)

Analysis Tool

- OrcaFlex

Aerodynamics

- BEM/GDW
- FDT (Filtered Dynamic Thrust)

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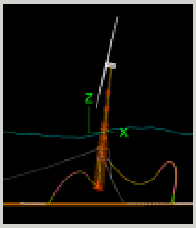
Model Comparison

- Deeplines: Structure/mooring design analysis (Dr Techn. Olav Olsen / Principia)
  - 10 RPM rotor
- OrcaFlex: Cable design analysis
  - Governing loadings on cable are local wave loads, current drag and offset
  - OrcaFlex/FAST: Rotor dynamics, BEM and Statoil controller
  - OrcaFlex/FDT: Point-load, aerodynamic integration (~6 times faster)
  - 11 RPM rotor defined by Statoil
- Comparison of motions near MSL
  - Cases defined in agreement with Statoil
  - Fixed Turbine
  - Decay test
  - Deeplines vs OrcaFlex
  - OrcaFlex/FAST vs OrcaFlex/FDT



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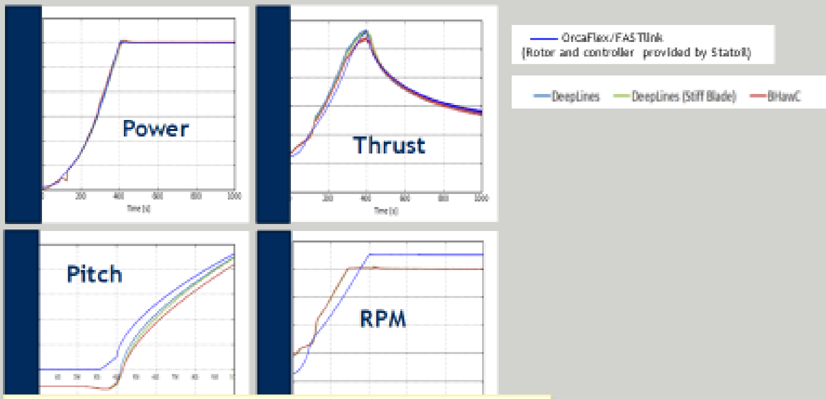
Fixed Turbine



Note: The rotors provided by Siemens and Statoil are not similar

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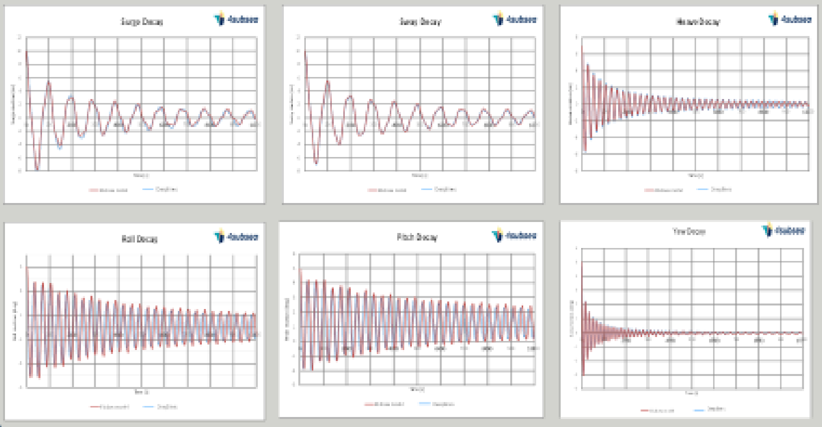
Decay Tests

Excellent match!



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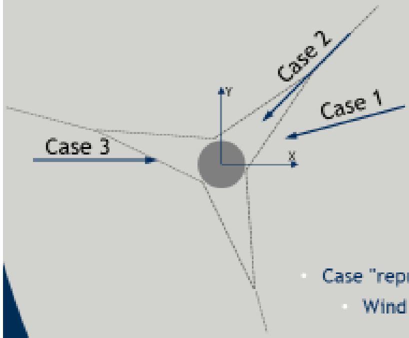
Comparison Cases

Deeplines vs. OrcaFlex (motion 1m below MSL)



1. **ULS, Parked Rotor**
   39.0m/s, 50yr Hs
2. **ULS, Operating Rotor**
   22.2m/s, 50yr Hs
3. **FLS Operating**
   14.0m/s, Low Hs

- Case "reproduced" in OrcaFlex
  - Wind and wave time series NOT identical, spectras similar

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Statistics, ULS, Operating

Operating, Updated ADC controller
Wind 22.2m/s, Uc 1.5m/s
Hs 10.0m, Tp 12.7s

- Notes:
  - Statistics are based on 10 seeds (10 x 3 hours)
  - Max and Min are 90th percentile from Gumbel distribution
  - OrcaFlex rotor/controller provided by Statoil

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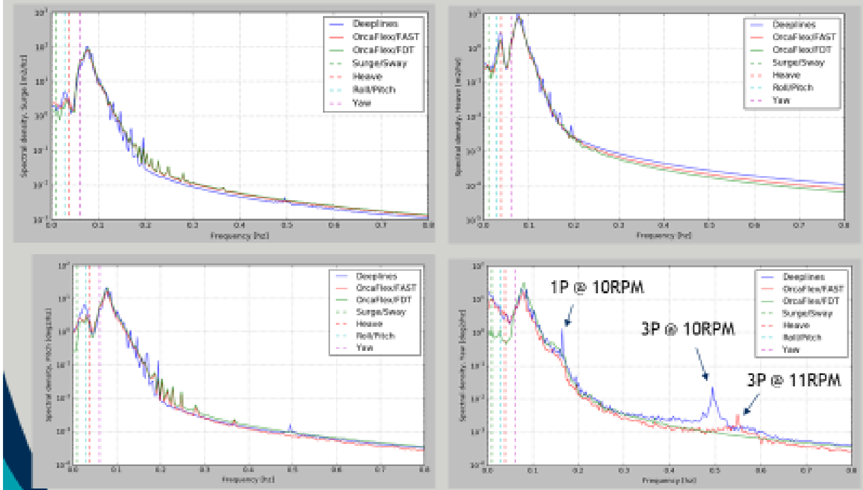
Spectra, ULS, Operating



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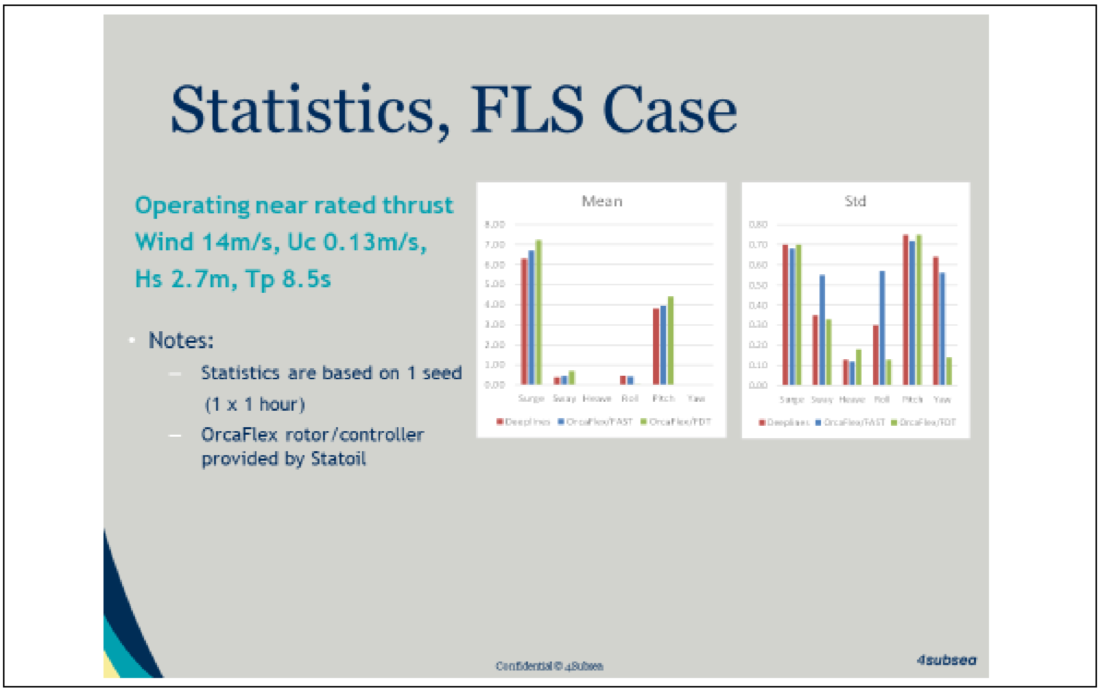
Statistics, FLS Case
Operating near rated thrust
Wind 14m/s, Uc 0.13m/s,
Hs 2.7m, Tp 8.5s
Notes:
Statistics are based on 1 seed (1 x 1 hour)
OrcaFlex rotor/controller provided by Statoil
Mean
Std
Surge Sway Heave Roll Pitch Yaw
Deeplines OrcaFlex/FAST OrcaFlex/FDT
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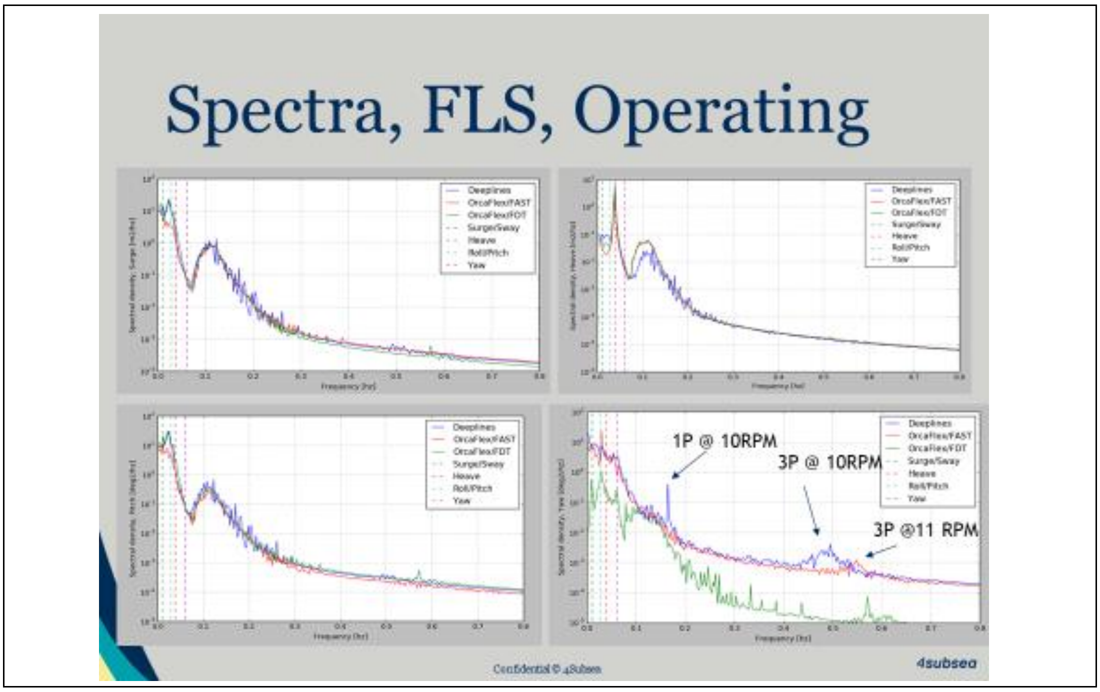
Spectra, FLS, Operating
Deeplines
OrcaFlex/FAST
OrcaFlex/FDT
Surge/Sway
Heave
Roll/Pitch
Yaw
1P @ 10RPM
3P @ 10RPM
3P @11 RPM
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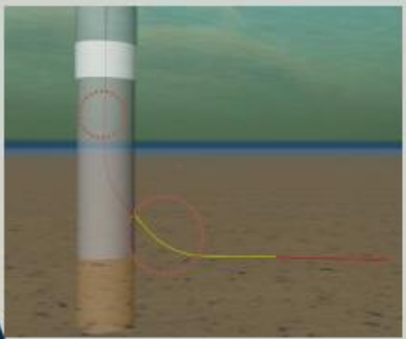
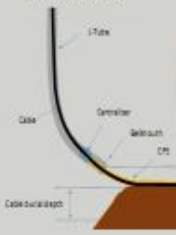
Closing Remarks on "Static" Cables
(not always static)

Tyical hotspots



Important factors

Cross section design (SN!)
Cable Protection System (CPS)
Scour
Installation
Soil
Kinematics



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Thank you.

4subsea

Validation for a Multi-Fidelity Structural Analysis Process

Martin Rädel, Christian Willberg

German Aerospace Center (DLR)
Institute of Composite Structures and Adaptive Systems
Department Structural Mechanics

IEA Wind, Task 11
Topical Expert Meeting #88
Edinburgh, 07.09.2017

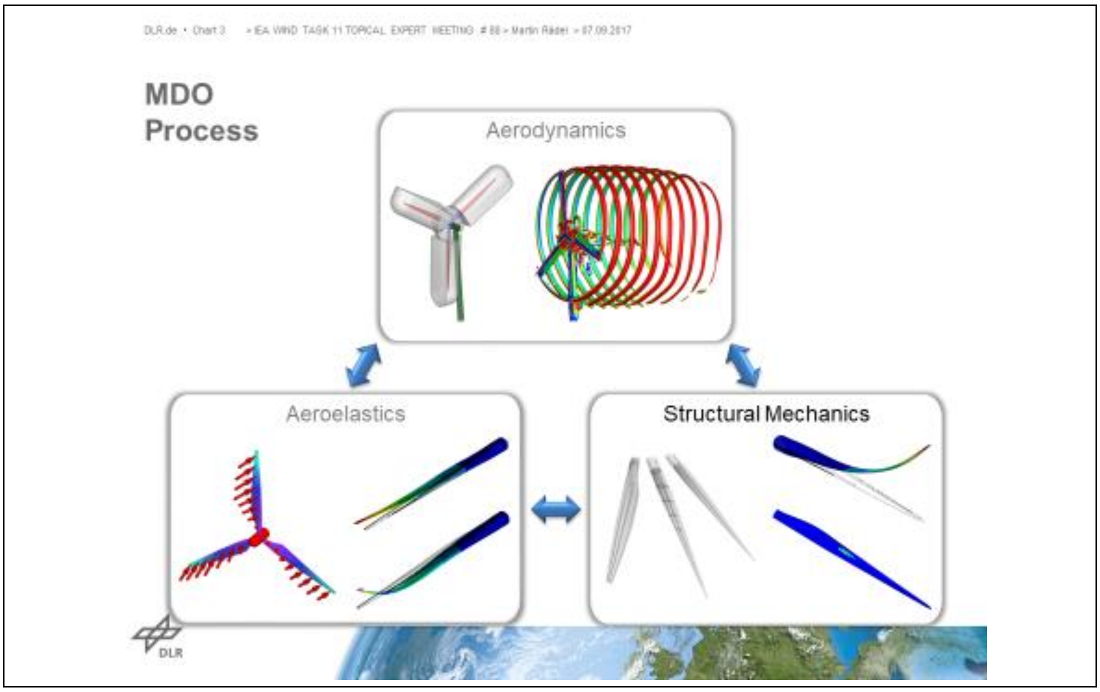
Knowledge for Tomorrow

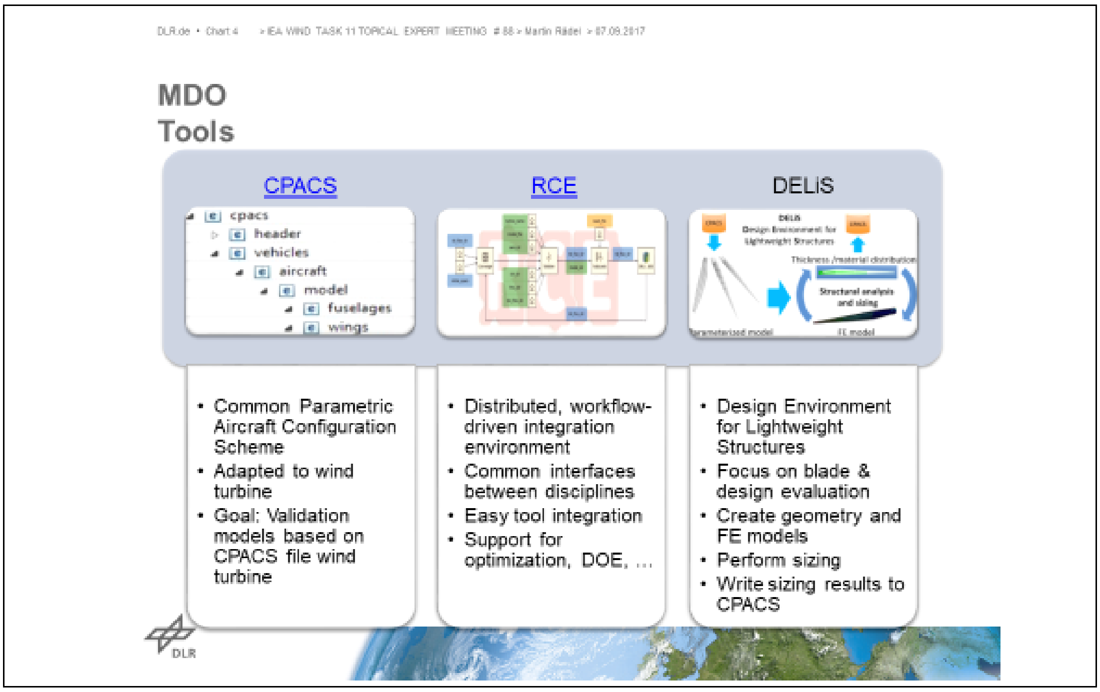
DLR

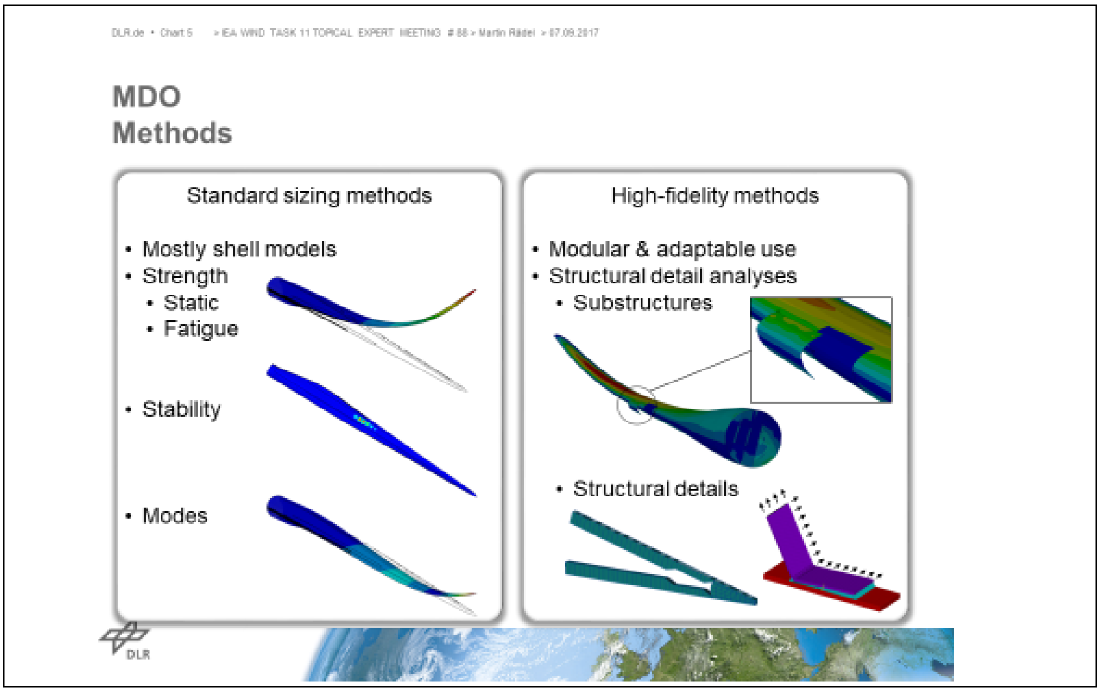
Outline

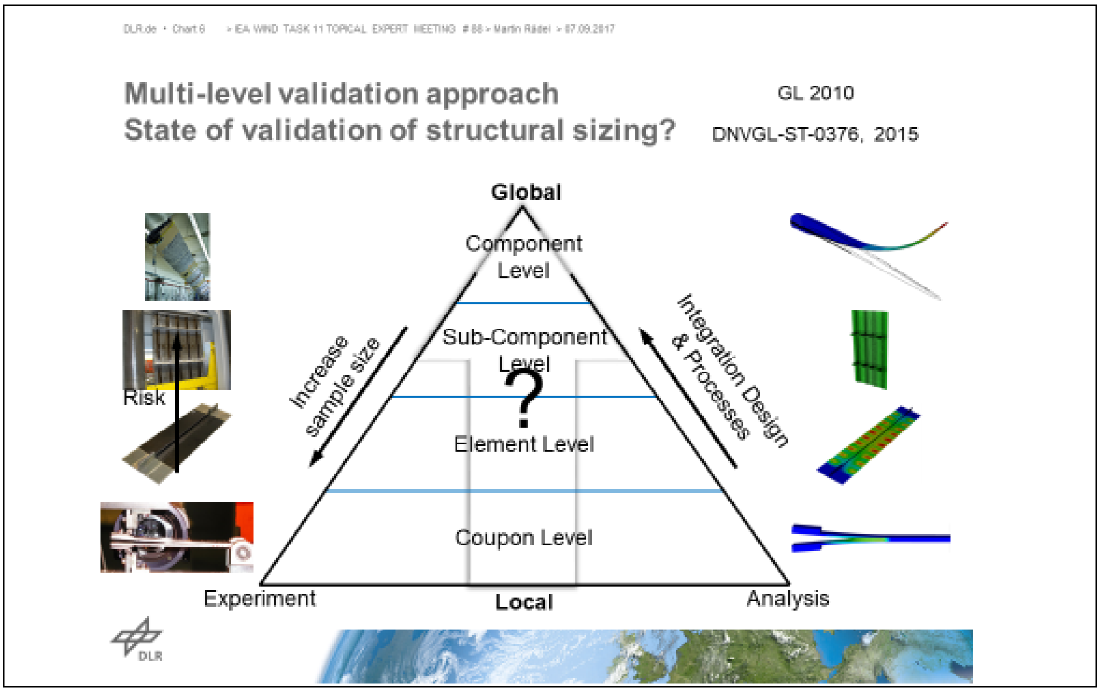
- Context
- Multidisciplinary optimization (MDO)
  - Process
  - Tools
  - Methods
- Multi-level validation approach
  - State of validation of structural sizing
  - Examples @ DLR & partners
- In-situ monitoring & validation
- Conclusions

DLR


DLR.de • Chart 3 > IEA WIND TASK 11 TOPICAL EXPERT MEETING # 88 > Martin Rädel > 07.09.2017
MDO
Process
Aerodynamics
Aeroelastics
Structural Mechanics
DLR


DLR.de • Chart 4 > IEA WIND TASK 11 TOPICAL EXPERT MEETING # 88 > Martin Rädel > 07.09.2017
MDO
Tools
CPACS
RCE
DELiS
cpacs
header
vehicles
aircraft
model
fuselages
wings
• Common Parametric Aircraft Configuration Scheme
• Adapted to wind turbine
• Goal: Validation models based on CPACS file wind turbine
• Distributed, workflow-driven integration environment
• Common interfaces between disciplines
• Easy tool integration
• Support for optimization, DOE, …
• Design Environment for Lightweight Structures
• Focus on blade & design evaluation
• Create geometry and FE models
• Perform sizing
• Write sizing results to CPACS
DLR

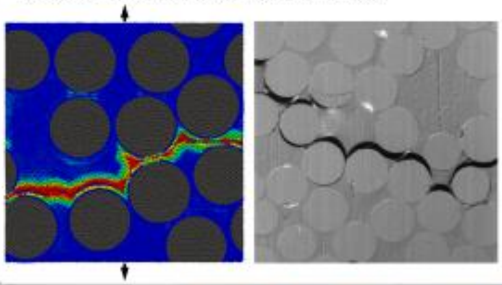

DLR.de • Chart 5 > IEA WIND TASK 11 TOPICAL EXPERT MEETING # 88 > Martin Rädel > 07.09.2017
MDO
Methods
Standard sizing methods
• Mostly shell models
• Strength
• Static
• Fatigue
• Stability
• Modes
High-fidelity methods
• Modular & adaptable use
• Structural detail analyses
• Substructures
• Structural details
DLR


DLR.de • Chart 6 > IEA WIND TASK 11 TOPICAL EXPERT MEETING # 88 > Martin Rädel > 07.09.2017
Multi-level validation approach
State of validation of structural sizing?
GL 2010
DNVGL-ST-0376, 2015
Global
Component Level
Sub-Component Level
?
Element Level
Coupon Level
Local
Experiment
Analysis
Increase sample size
Integration Design & Processes
Risk
DLR

Multi-level validation approach
Examples @ DLR & partners

Coupon level

- Characterization of advanced model parameters for high-fidelity methods, e.g. material models
- Validation/Verification for advanced simulation methods for future hi-fi-methods in MDO



Element level

Sub-Component level

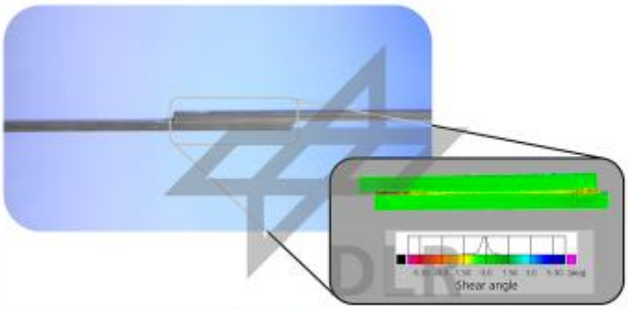
Component level

Multi-level validation approach
Examples @ DLR & partners

Coupon level

Element level

- Characterization of structural element/details
- Fast assessment of new structural approaches



Sub-Component level

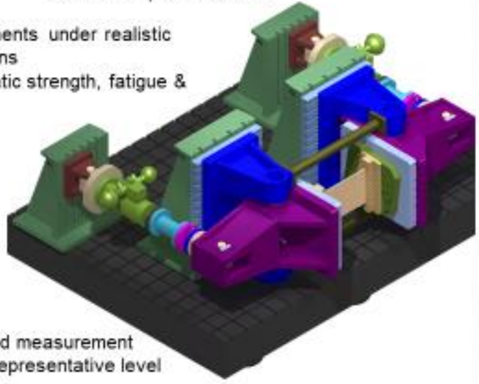
Component level

Multi-level validation approach
Examples @ DLR & partners

Coupon level | Element level | Sub-Component level | Component level

Sub-Component level

- Test subcomponents under realistic loading conditions
- Coverage of static strength, fatigue & stability tests



- Test of advanced measurement techniques on representative level

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Multi-level validation approach
Examples @ DLR & partners

Coupon level | Element level | Sub-Component level | Component level

Component level

- Final stage of system validation
- Currently building 20m blade
- Testing @ Fraunhofer IWES

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In-situ monitoring & validation
Examples

- Element & sub-component level tests → Potentials for technology validation
- Enable path to SHM, in-situ validation, EoD analysis

SHM
- Piezoceramic actuators
- Evaluation under realistic loading

In-situ validation
- FBG sensors of B-PHOT, VUB
- 3D-ε-measurements
- Along full production- & life-cycle

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Conclusions

- MDO process for optimal configurations
- Need for validation in earlier design stages of rotor blades
- Common model format & data structure simplifies tool & method integration
- Element & sub-component testing for method & design validation & verification
- Possible intermediate steps in certification
- Enabler for testing of advanced measurement techniques
- Health monitoring & in-situ validation for safer operation

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Thank you for your attention.

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  Institute of Composite Structures and Adaptive Systems
  Department Structural Mechanics

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  D-38108 Braunschweig
  Germany

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  Telefax: +49 (0)531 295-2232
  E-Mail: martin.raedel@dlr.de
  Internet: www.DLR.de/fa

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3D CFD Simulations in Comparisson to Large Scale Tests for Various Types of Breaking Waves

- Capabilities and Limitations -

Arndt Hildebrandt
Ludwig-Franzius-Institute for Hydraulic, Estuarine & Coastal Engineering

Outline

- Physical Model Tests
- Numerical Modelling
  + Wave Propagation
  + Wave Transformation
  + Wave Impact
- Example for spatial pressure development:
  Maximum pressures and their positions
  Range of impact
- Capabilities and Limitations

Physical model tests:

Borken wave (Load Case 1)

- Turbulent, foamy front

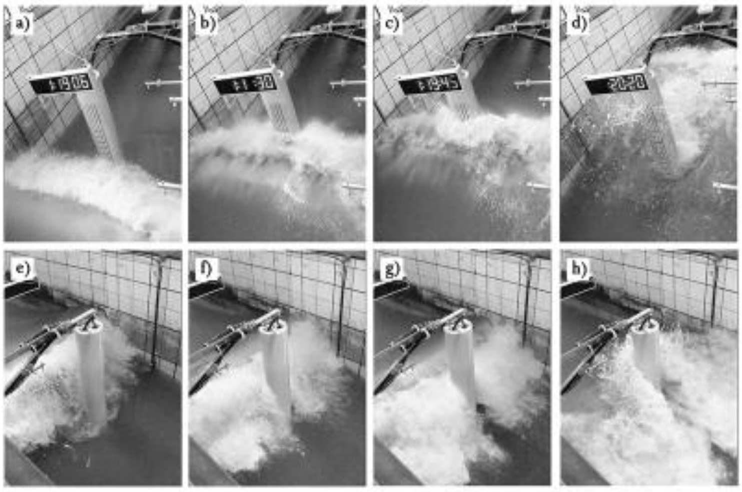
Curled wave front (Load Case 2)

- Horizontal water jet

Vertical wave front (Load Case 3)

- Partly vertical wave front

Borken wave (LC 1):



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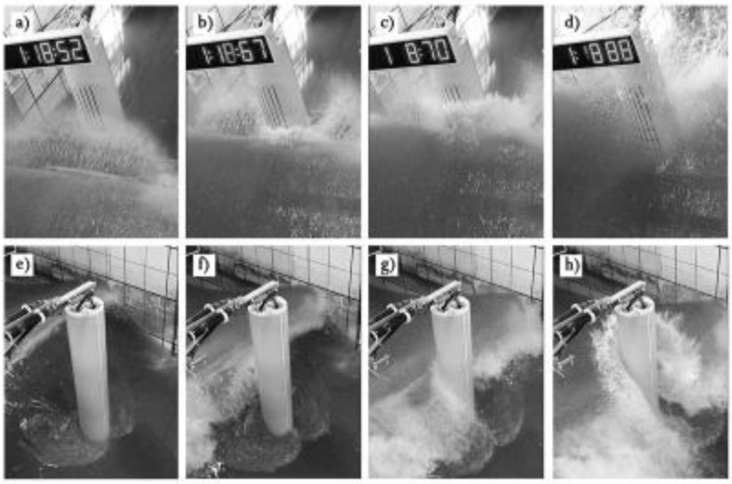
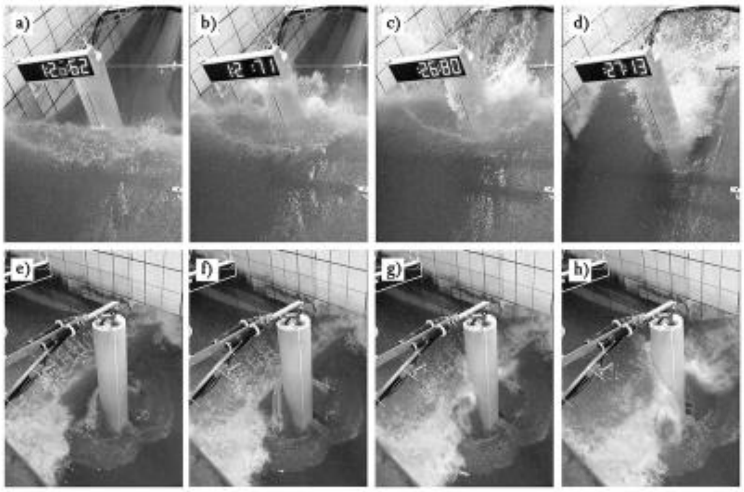
Curled wave front (LC 2):



Vertical wave front (LC 3):



Physical model tests:

Borken wave (Load Case 1)

- Turbulent, foamy front
- Entrapped air

Curled wave front (Load Case 2)

- Horizontal water jet
- Less air in wave crest

Vertical wave front (Load Case 3)

- Partly vertical wave front
- Nearly no entrapped air

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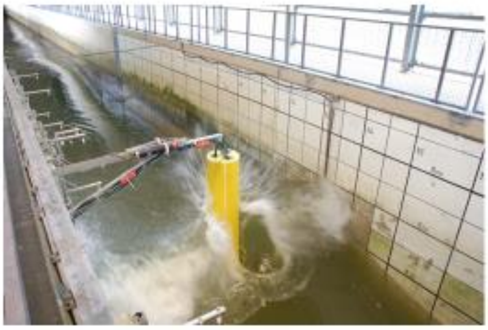
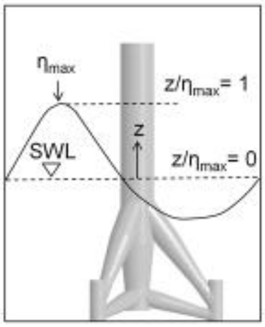
GWK experiments:





- Scale 1:12
- Diameter D = 0.50 m
- Water depth d = 2.50 m
- Breaker height $\overline{H}$ = 1.46 m
- Breaker period $\overline{T}$ = 4.08 s

  (transient wave)

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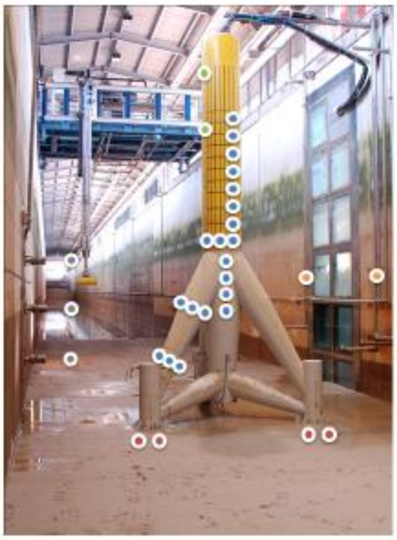
GWK experiments:

- 30 Pressure sensors (PS)
  => Vertical profile, 14+4 PS
  => Horizontal profile with 7 PS
  => Upper braces with 6 PS
- 2 Acceleration meters (xyz)
- 8 Strain gauges
- Current meters
  => 2 x 3 NSW probes (xz)
- Water elevation
  => 24 Wave gauges
- Cameras (front-, back view)
  => Wave runup, wave geometry



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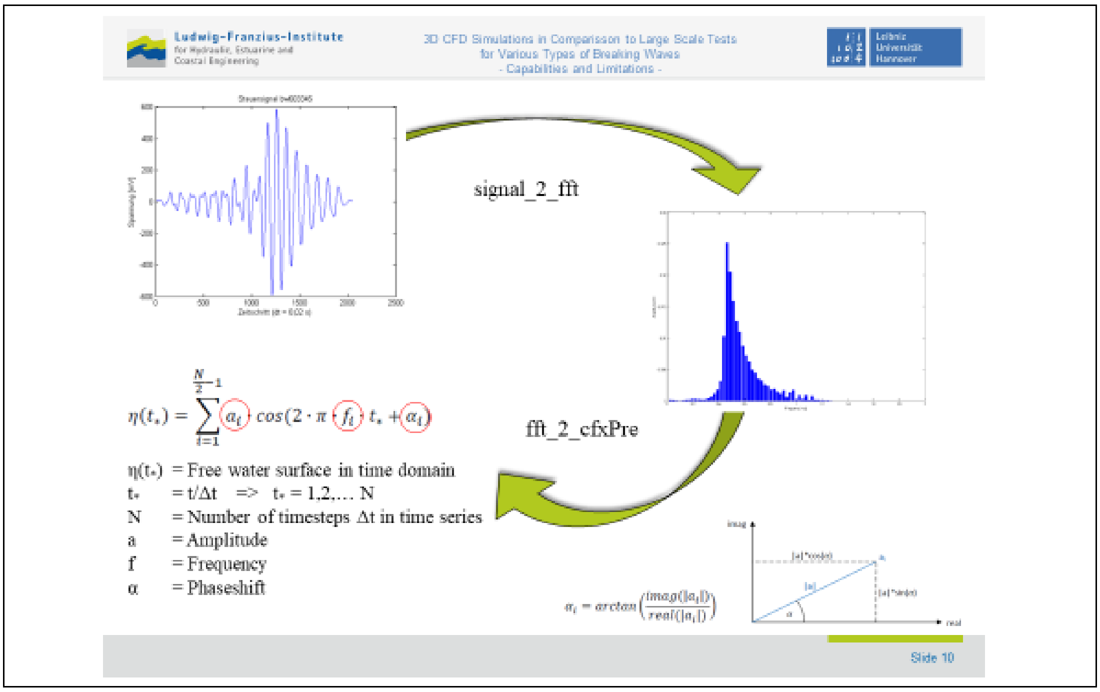
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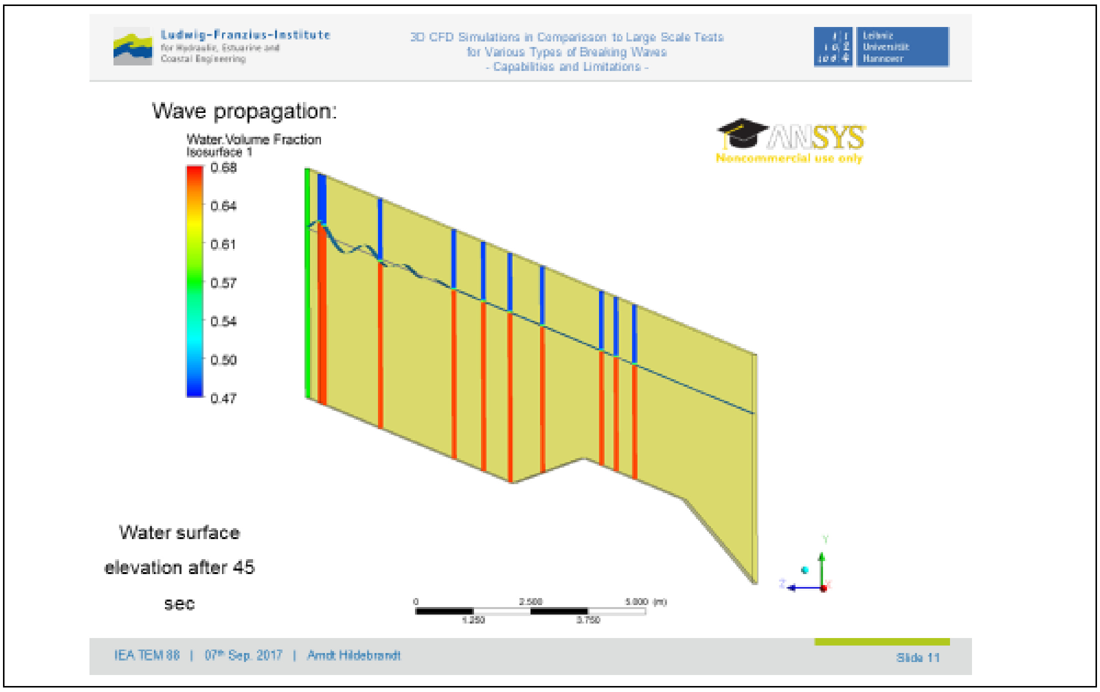
signal_2_fft
fft_2_cfxPre
$\eta(t_*) = \sum_{i=1}^{\frac{N}{2}-1} a_i \cos(2 \cdot \pi \cdot f_i \cdot t_* + \alpha_i)$
η(t*) = Free water surface in time domain
t* = t/Δt => t* = 1,2,… N
N = Number of timesteps Δt in time series
a = Amplitude
f = Frequency
α = Phaseshift
$\alpha_i = arctan\left(\frac{imag(|a_i|)}{real(|a_i|)}\right)$
imag
real
Slide 10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Wave propagation:
Water.Volume Fraction
Isosurface 1
0.68
0.64
0.61
0.57
0.54
0.50
0.47
ANSYS
Noncommercial use only
Water surface elevation after 45 sec
0
2.500
5.000 (m)
1.250
3.750
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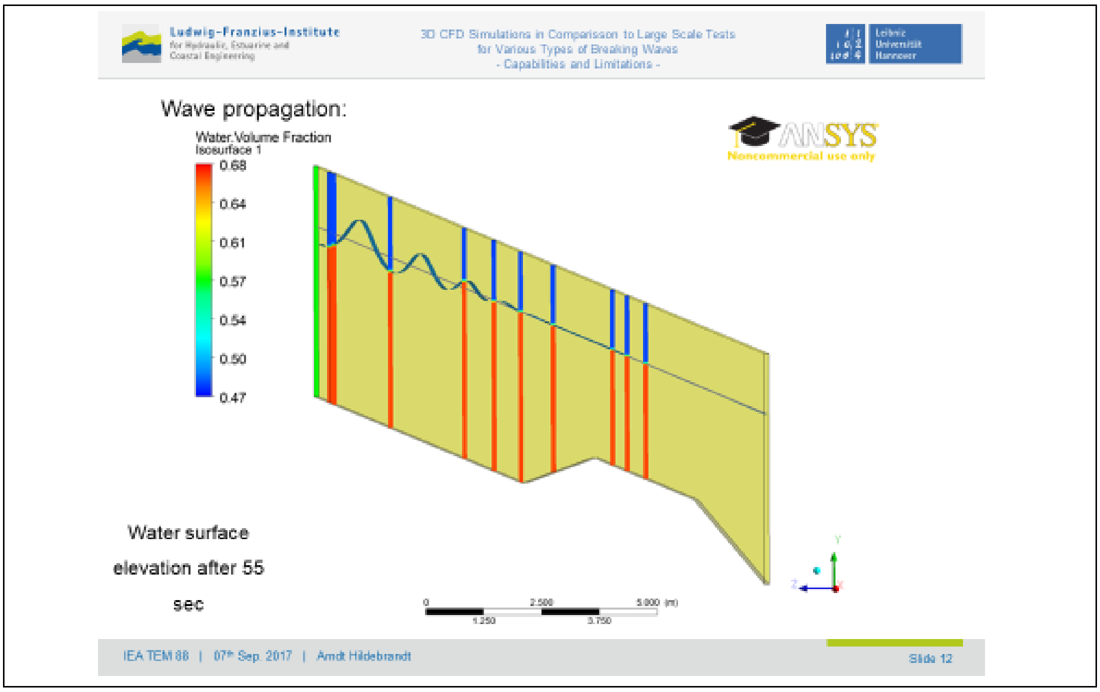

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Wave propagation:
Water.Volume Fraction
Isosurface 1
0.68
0.64
0.61
0.57
0.54
0.50
0.47
ANSYS
Noncommercial use only
Water surface
elevation after 55
sec
0
2.500
5.000 (m)
1.250
3.750
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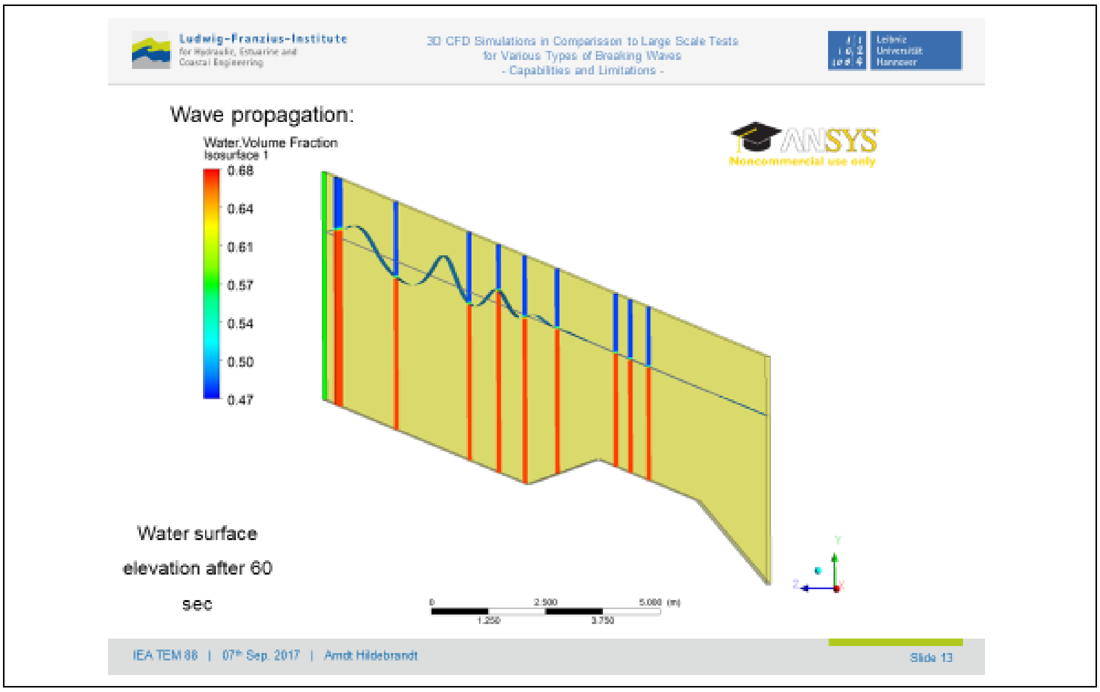

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- Capabilities and Limitations -
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Wave propagation:
Water.Volume Fraction
Isosurface 1
0.68
0.64
0.61
0.57
0.54
0.50
0.47
ANSYS
Noncommercial use only
Water surface
elevation after 60
sec
0
2.500
5.000 (m)
1.250
3.750
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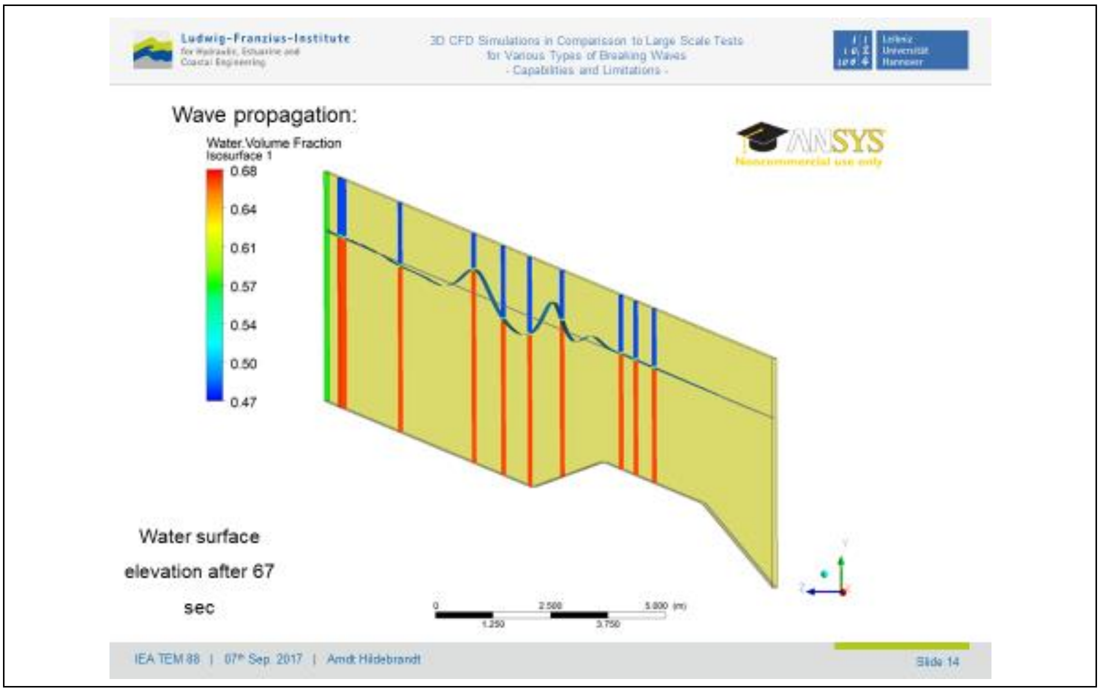
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Wave propagation:
Water.Volume Fraction
Isosurface 1
0.68
0.64
0.61
0.57
0.54
0.50
0.47
ANSYS
Noncommercial use only
Water surface elevation after 67 sec
0
1.250
2.500
3.750
5.000 (m)
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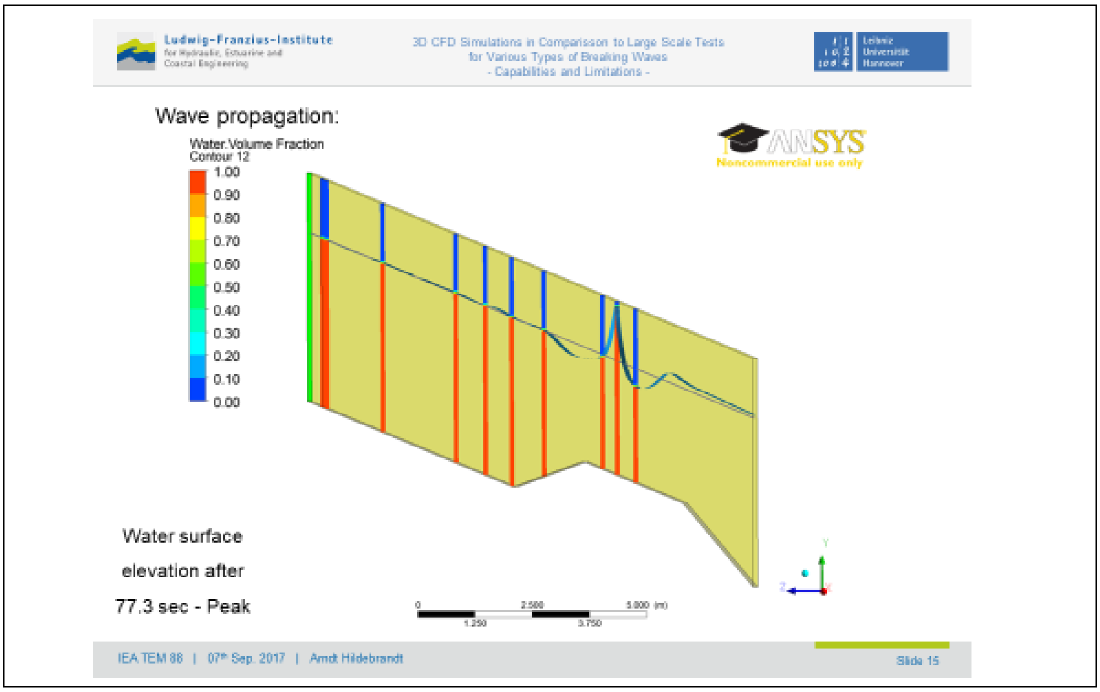
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Leibniz Universität Hannover
Wave propagation:
Water.Volume Fraction
Contour 12
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
ANSYS
Noncommercial use only
Water surface elevation after 77.3 sec - Peak
0
1.250
2.500
3.750
5.000 (m)
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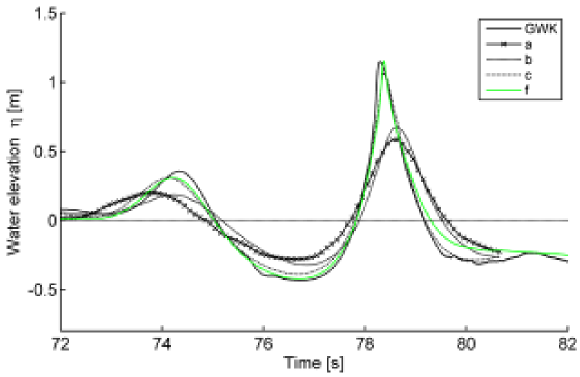
Wave propagation:

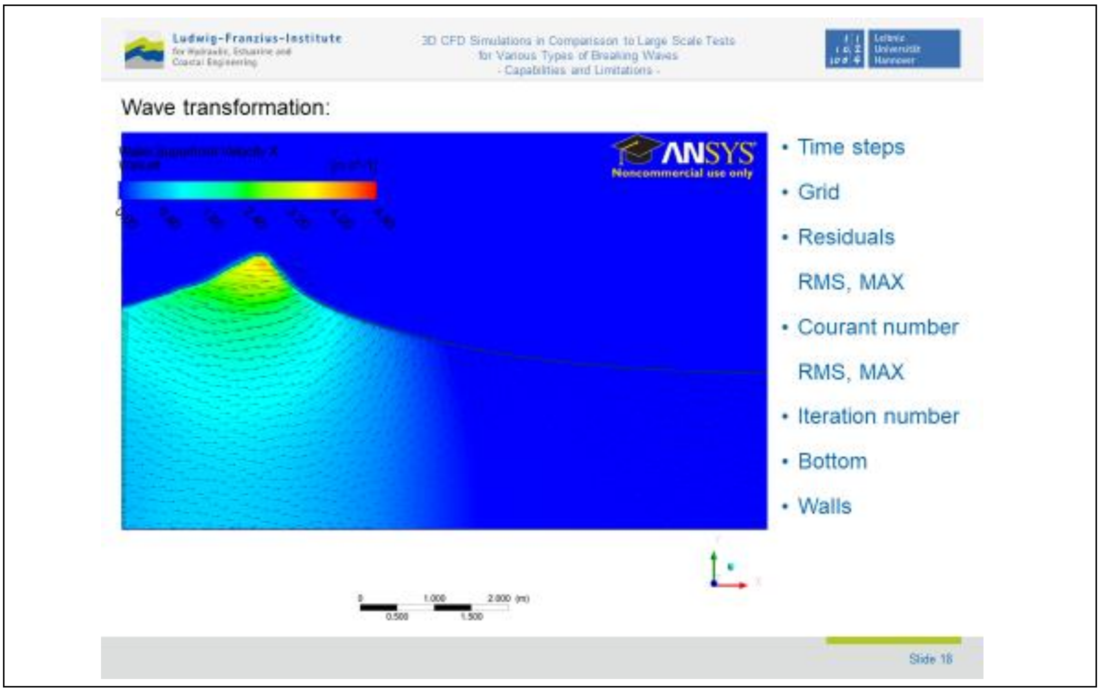


- Quasi 2D VOF model
  Cell height 1.3 cm
  Cell length 2.6 cm
- 2,625,000 Nodes
- 3,943,493 Elements
- Elements per meter H
  77
- Elements per meter L
  38

E/mH & E/mL

- Mesh a: 07 & 05
- Mesh b: 13 & 10
- Mesh c: 33 & 13

	Timestep dt Relative sample $f_r = T_{wave}$ / dt	C_{max}	C_{RMS}	Iter.
Mesh S: 8cm Size/H = 0.053	0.0005 8680	<0.2	<0.03	<3
	0.002/2170	1.2	<0.08	<6
	0.02/217	9	<0.6	<9
	0.05/86	23	<1.5	<10
Mesh M: 5cm Size/H = 0.033	0.0005 8680	<0.5	<0.02	<5
	0.002/2170	1.9	<0.09	<7
	0.02/217	20	0.7	<9
	0.05/86	48	1.8	<12
Mesh L: 3cm Size/H = 0.02	0.0005 8680	<0.4	<0.02	<5
	0.002/2170	2	<0.12	<4
	0.02/217	14	1.1	<10
	0.05/86	42	<4	<12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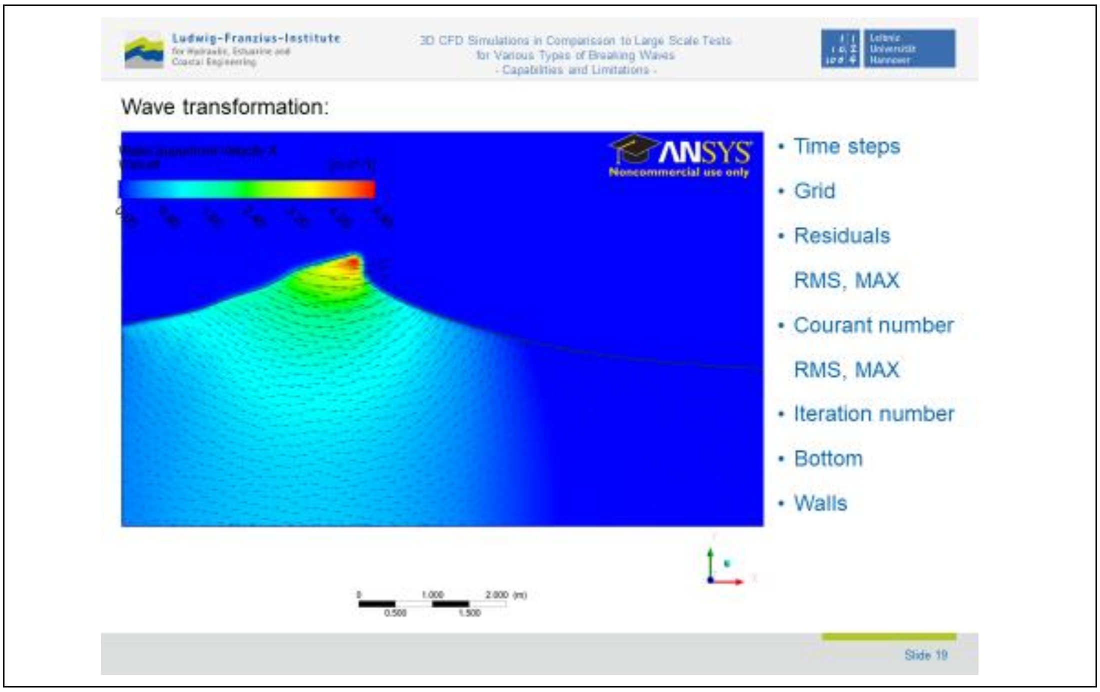
Wave transformation:
ANSYS
Noncommercial use only
• Time steps
• Grid
• Residuals
RMS, MAX
• Courant number
RMS, MAX
• Iteration number
• Bottom
• Walls
0
1.000
2.000 (m)
0.500
1.500
Slide 18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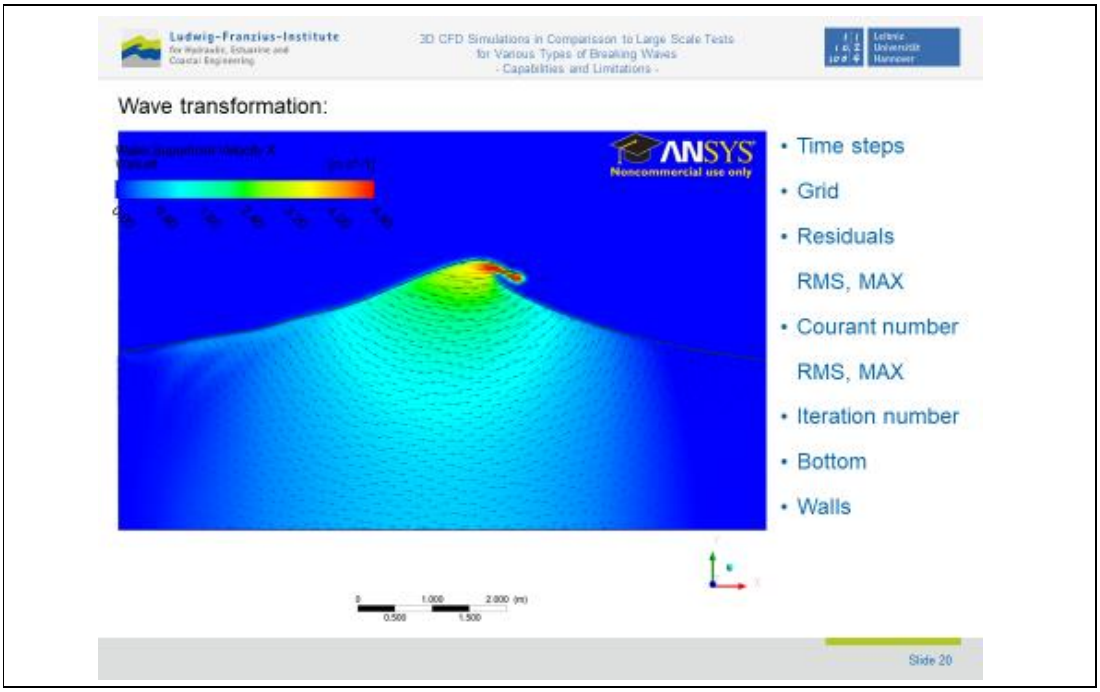
Wave transformation:
ANSYS
Noncommercial use only
• Time steps
• Grid
• Residuals
RMS, MAX
• Courant number
RMS, MAX
• Iteration number
• Bottom
• Walls
0
1.000
2.000 (m)
0.500
1.500
Slide 19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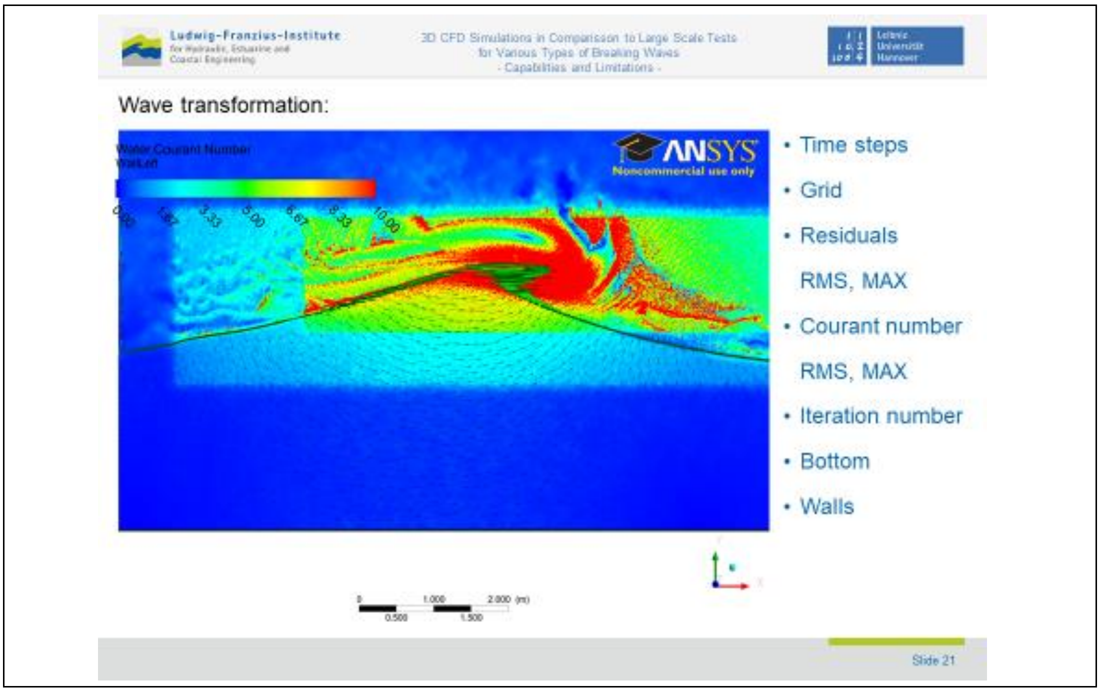
- Capabilities and Limitations -
Wave transformation:
ANSYS
Noncommercial use only
• Time steps
• Grid
• Residuals
RMS, MAX
• Courant number
RMS, MAX
• Iteration number
• Bottom
• Walls
Slide 20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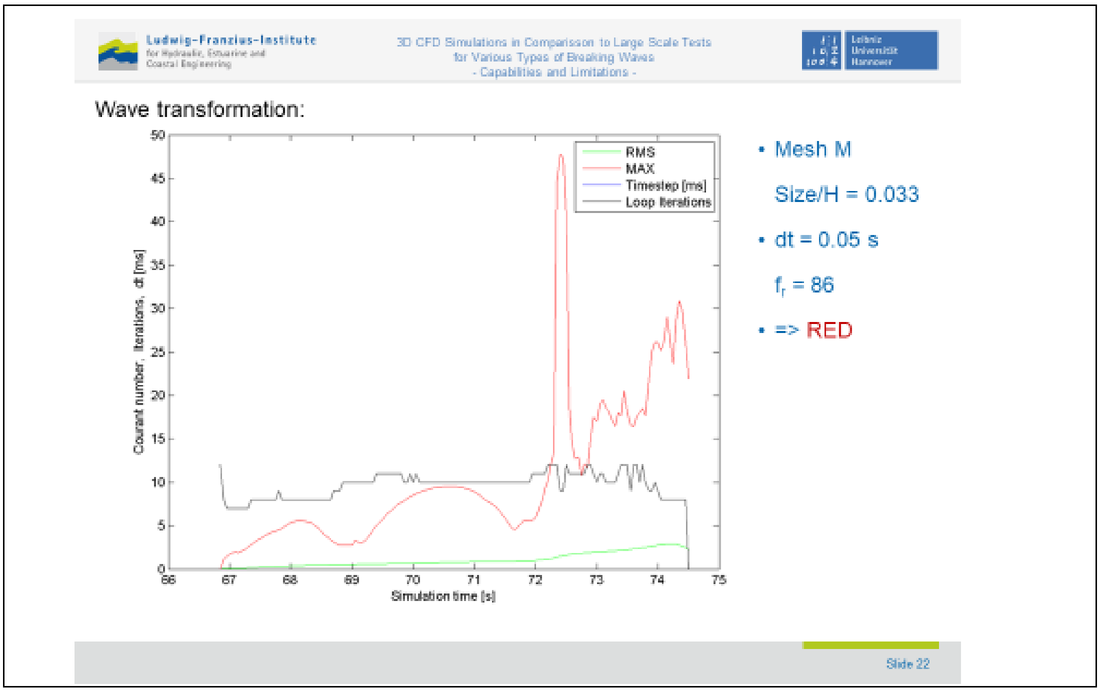
for Various Types of Breaking Waves
- Capabilities and Limitations -
Wave transformation:
ANSYS
Noncommercial use only
Water.Courant Number
0.00
1.67
3.33
5.00
6.67
8.33
10.00
• Time steps
• Grid
• Residuals
RMS, MAX
• Courant number
RMS, MAX
• Iteration number
• Bottom
• Walls
Slide 21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for Various Types of Breaking Waves
- Capabilities and Limitations -
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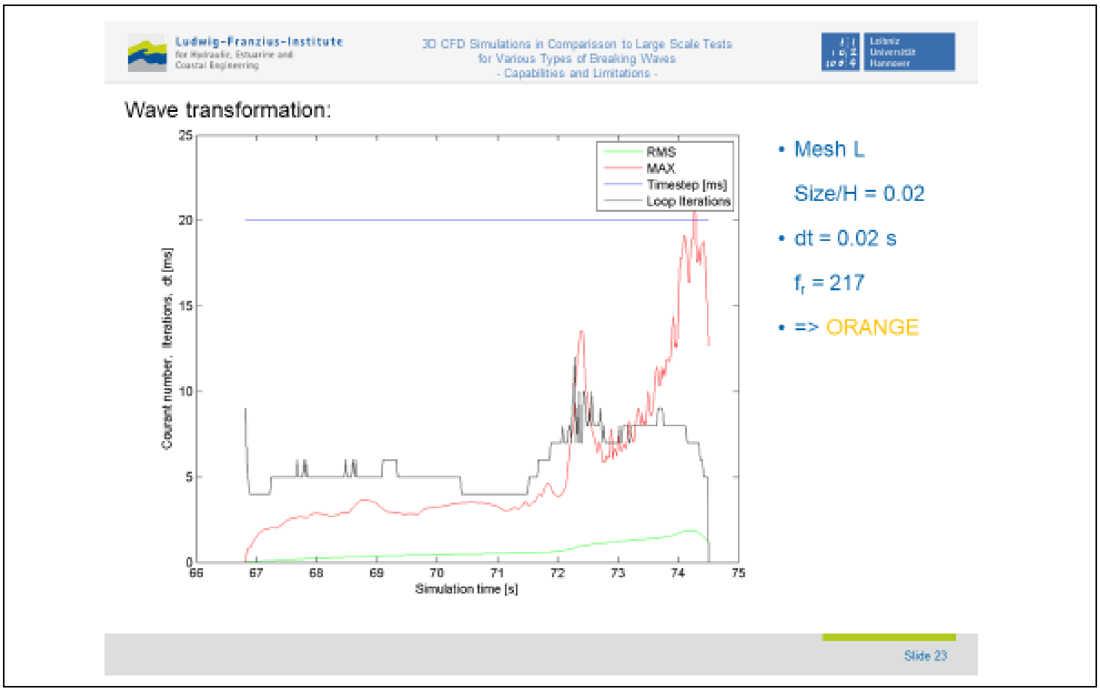
Wave transformation:
RMS
MAX
Timestep [ms]
Loop Iterations
Courant number, Iterations, dt [ms]
Simulation time [s]
• Mesh M
Size/H = 0.033
• dt = 0.05 s
f_r = 86
• => RED
Slide 22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- Capabilities and Limitations -
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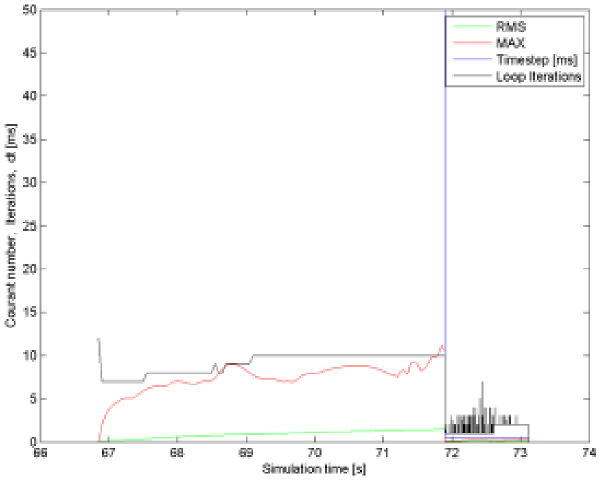
Wave transformation:
RMS
MAX
Timestep [ms]
Loop Iterations
Courant number, Iterations, dt [ms]
Simulation time [s]
• Mesh L
Size/H = 0.02
• dt = 0.02 s
f_r = 217
• => ORANGE
Slide 23

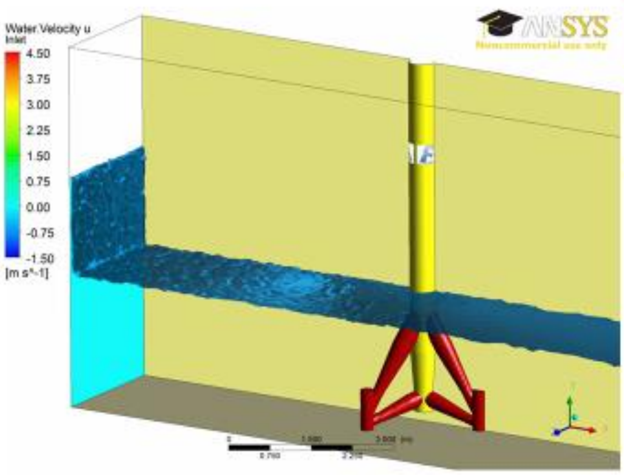
Wave transformation:

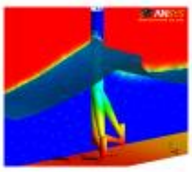


- Mesh L

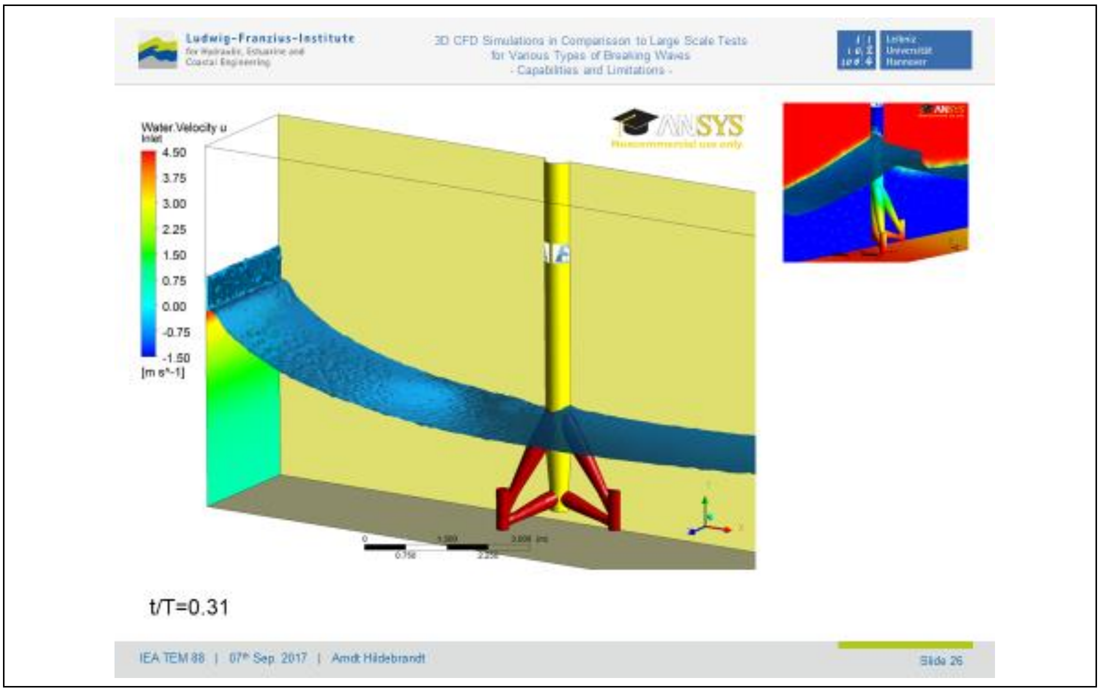
  Size/H = 0.02
- dt = 0.02 s

  f_r = 8680
- => GREEN





t/T=0.0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for Various Types of Breaking Waves
- Capabilities and Limitations -
Leibniz Universität Hannover
Water Velocity u
Inlet
4.50
3.75
3.00
2.25
1.50
0.75
0.00
-0.75
-1.50
[m s^-1]
ANSYS
t/T=0.31
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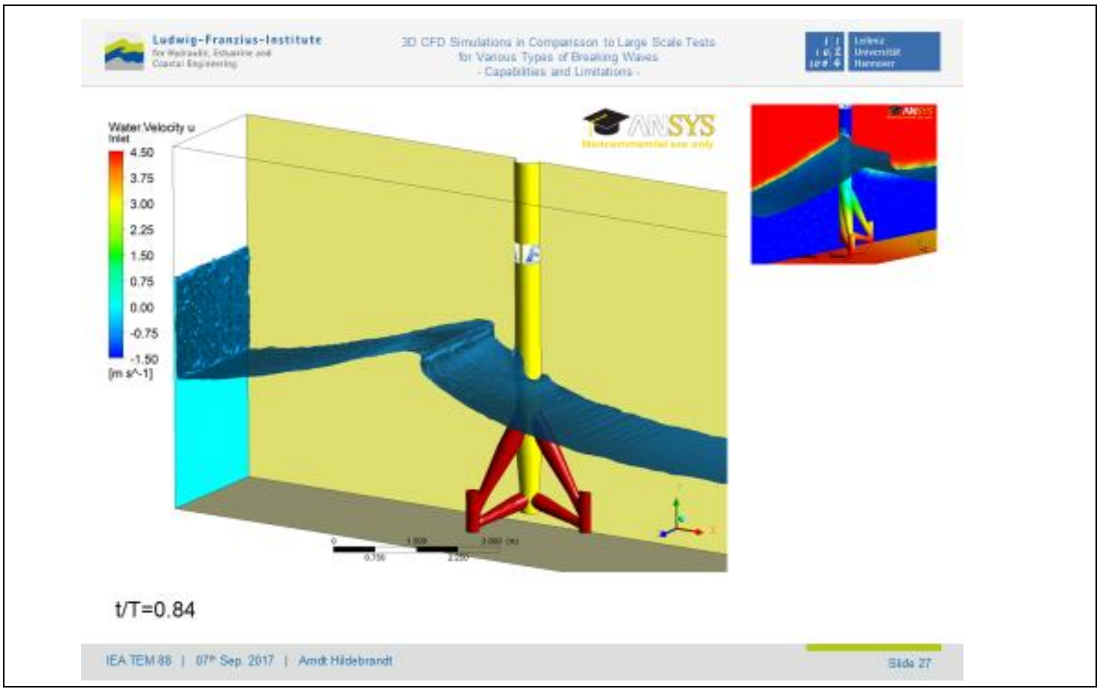
Slide 26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for Various Types of Breaking Waves
- Capabilities and Limitations -
Leibniz Universität Hannover
Water Velocity u
Inlet
4.50
3.75
3.00
2.25
1.50
0.75
0.00
-0.75
-1.50
[m s^-1]
ANSYS
t/T=0.84
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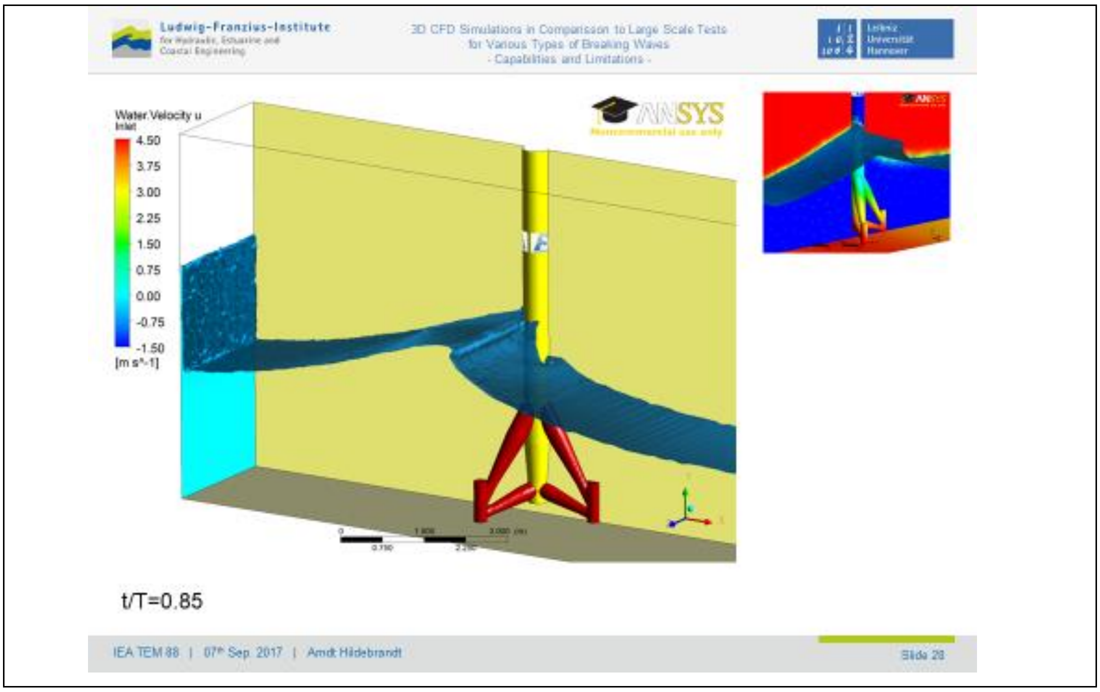
Slide 27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for Various Types of Breaking Waves
- Capabilities and Limitations -
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Water.Velocity u
Inlet
4.50
3.75
3.00
2.25
1.50
0.75
0.00
-0.75
-1.50
[m s^-1]
ANSYS
t/T=0.85
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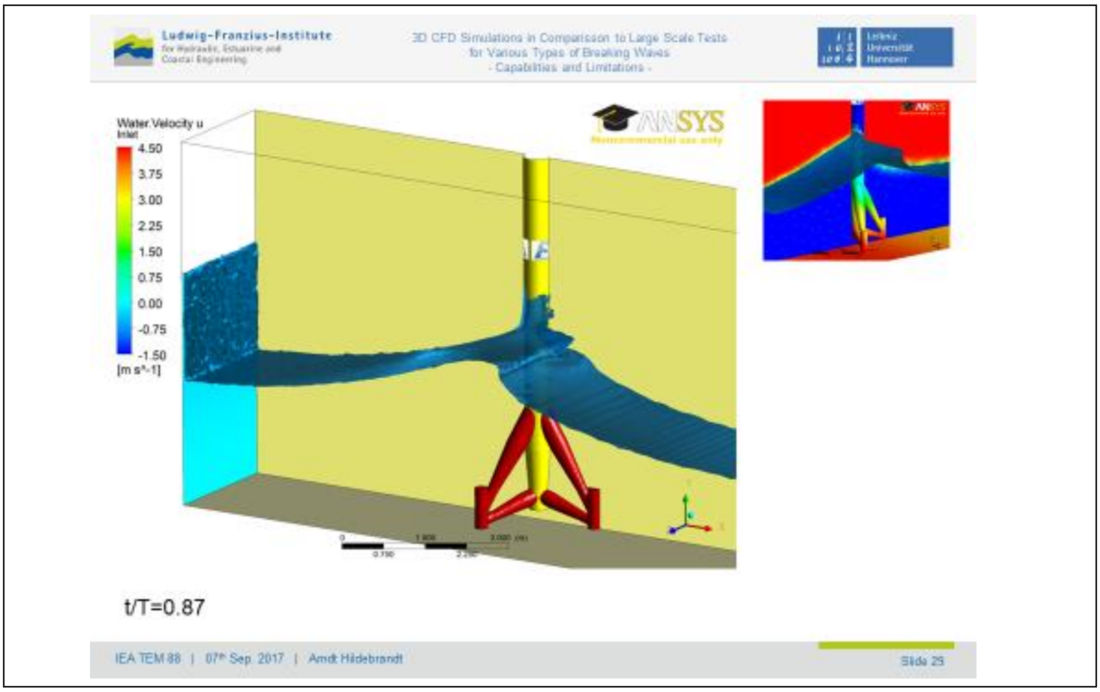
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- Capabilities and Limitations -
Leibniz Universität Hannover
Water.Velocity u
Inlet
4.50
3.75
3.00
2.25
1.50
0.75
0.00
-0.75
-1.50
[m s^-1]
ANSYS
t/T=0.87
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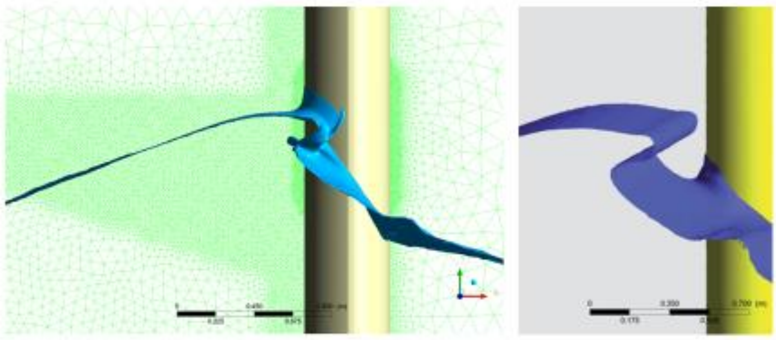
Slide 29

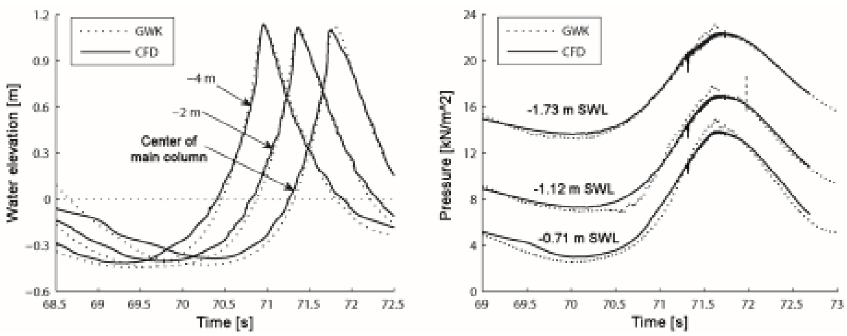
Wave impact:

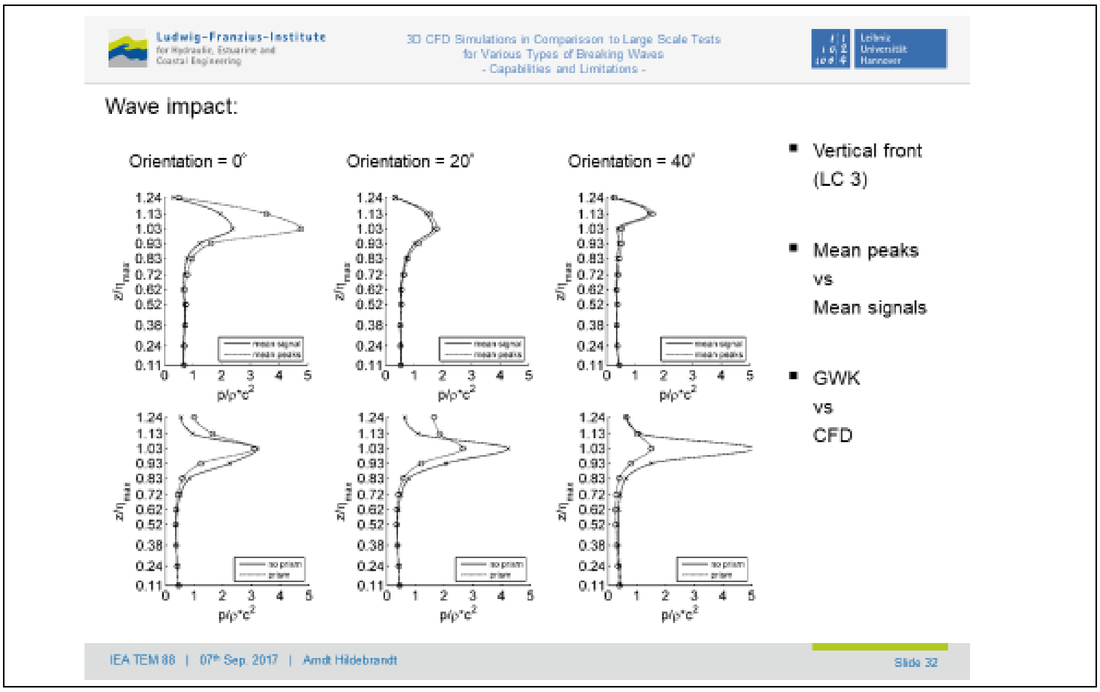
- Cell sizes: < 1 cm, 3 cm up to 10 cm
  Time steps: 0.0001 s up to 0.01 s
- Symmetry
- Average: ≈ 100 nodes per meter
- 1 week with 24 CPUs for 8 s
- 24 h with 12 CPUs for impact

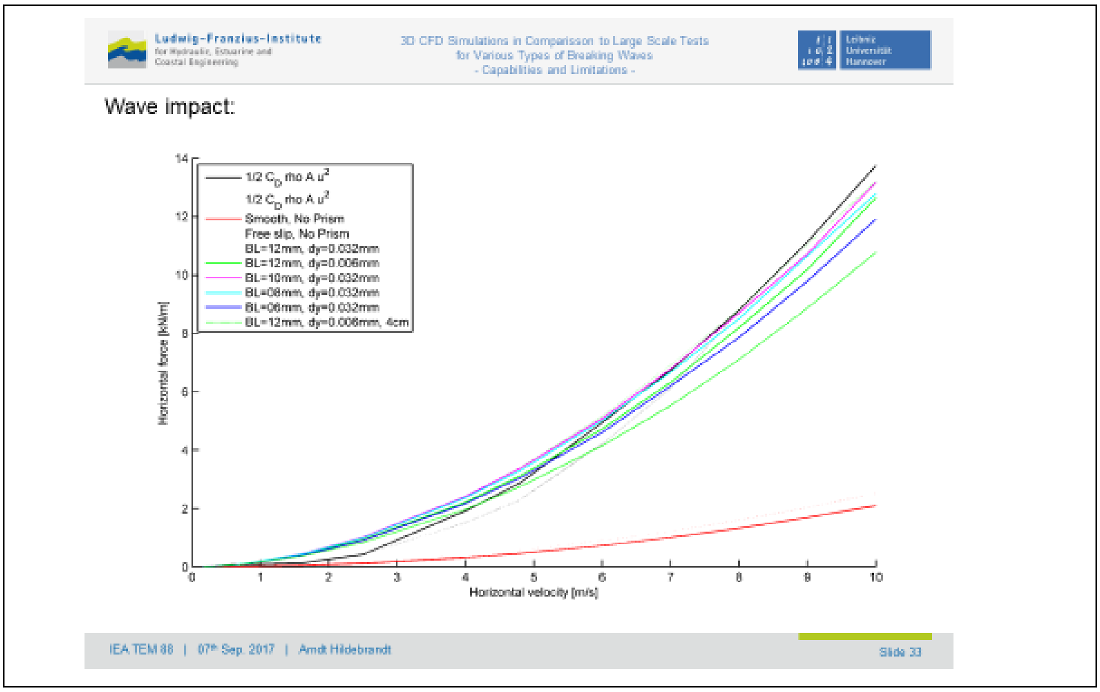


Wave impact:

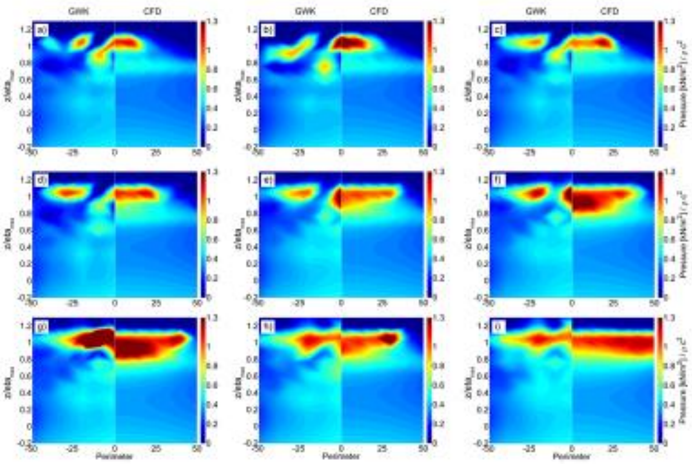
- Cell sizes: < 1 cm, 3 cm up to 10 cm
  Time steps: 0.0001 s up to 0.01 s
- Symmetry
- Average: ≈ 100 nodes per meter
- 1 week with 24 CPUs for 8 s
- 24 h with 12 CPUs for impact




Ludwig-Franzius-Institute
for Hydraulic, Estuarine and Coastal Engineering
3D CFD Simulations in Comparisson to Large Scale Tests
for Various Types of Breaking Waves
- Capabilities and Limitations -
Leibniz Universität Hannover
Wave impact:
Orientation = 0°
Orientation = 20°
Orientation = 40°
z/η_max
p/ρ*c²
mean signal
mean peaks
no prism
prism
Vertical front
(LC 3)
Mean peaks
vs
Mean signals
GWK
vs
CFD
IEA TEM 88 | 07th Sep. 2017 | Arndt Hildebrandt
Slide 32


Ludwig-Franzius-Institute
for Hydraulic, Estuarine and Coastal Engineering
3D CFD Simulations in Comparisson to Large Scale Tests
for Various Types of Breaking Waves
- Capabilities and Limitations -
Leibniz Universität Hannover
Wave impact:
1/2 C_D rho A u²
1/2 C_D rho A u²
Smooth, No Prism
Free slip, No Prism
BL=12mm, dy=0.032mm
BL=12mm, dy=0.006mm
BL=10mm, dy=0.032mm
BL=08mm, dy=0.032mm
BL=06mm, dy=0.032mm
BL=12mm, dy=0.006mm, 4cm
Horizontal force [kN/m]
Horizontal velocity [m/s]
IEA TEM 88 | 07th Sep. 2017 | Arndt Hildebrandt
Slide 33

Wave impact:



LC 2:

t/(R/c):

a) 0.01
b) 0.03
c) 0.05
d) 0.10
e) 0.15
f) 0.20
g) 0.25
h) 0.35
i) 0.45

Summary & perspectives

- Capabilities:
  + CFD models provide access to the complete flow domain, wave kinematic
  + Detailed load analysis:

	LC 3	LC 2	LC 1
Max C_S	4	3	2.7
Curling F	0.3	0.2	0.2
Rel. Height	1	0.9	0.7

- Limitations:
  - Mesh density around wave front and crest: Element size/wave height = 0.02-0.03
  - The relative time steps should be >= 2000 steps per period with regard to the onset of curling and the subsequent formation of the jet.
  - Air entrainment

- Perspective & further studies:

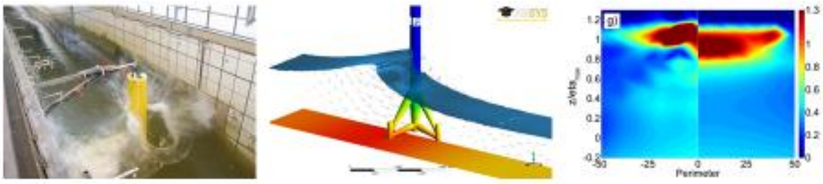
  Shear stresses and roughness of pile => marine growth

  Influence of substructures on impact loads and modelling parameters

Ludwig-Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering

3D CFD Simulations in Comparison to Large Scale Tests for Various Types of Breaking Waves - Capabilities and Limitations -

Leibniz Universität Hannover



Thank you for your attention!

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

RAVE RESEARCH AT ALPHA VENTUS

ForWind Zentrum für Windenergieforschung

IEA TEM 88 | 07th Sep. 2017 | Arndt Hildebrandt

Slide 36

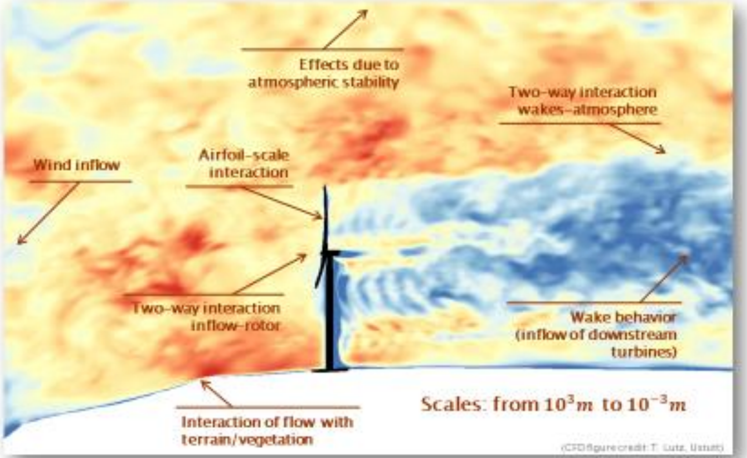
Technische Universität München
Wind Energy Institute

The Role of Wind Tunnel Testing in the Validation and Calibration of Models

Carlo L. Bottasso
Technische Universität München
& Politecnico di Milano

IEA Wind Task 11, Edinburgh, 6–8 September 2017

The Wind Inflow and its Interaction with the Wind Turbine



TUM Scaled Wind Farm Facility

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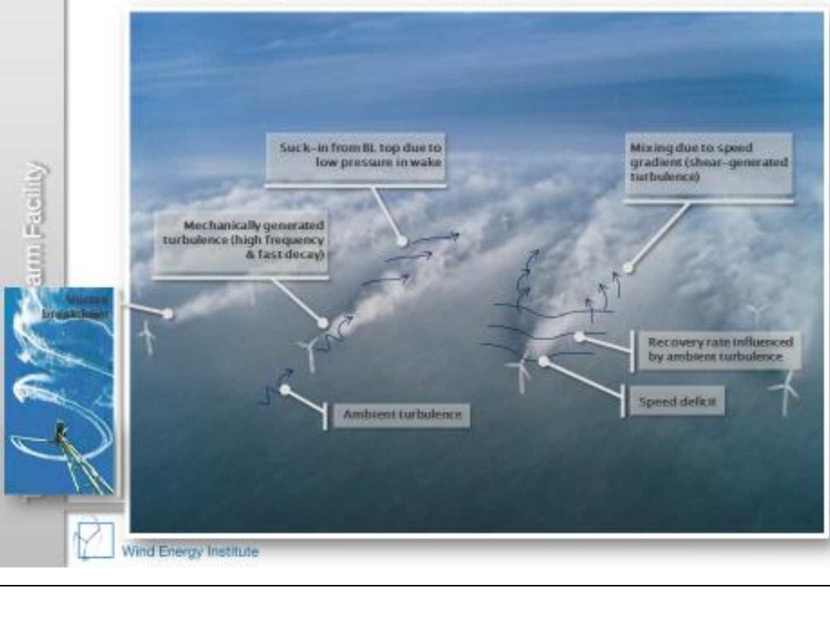
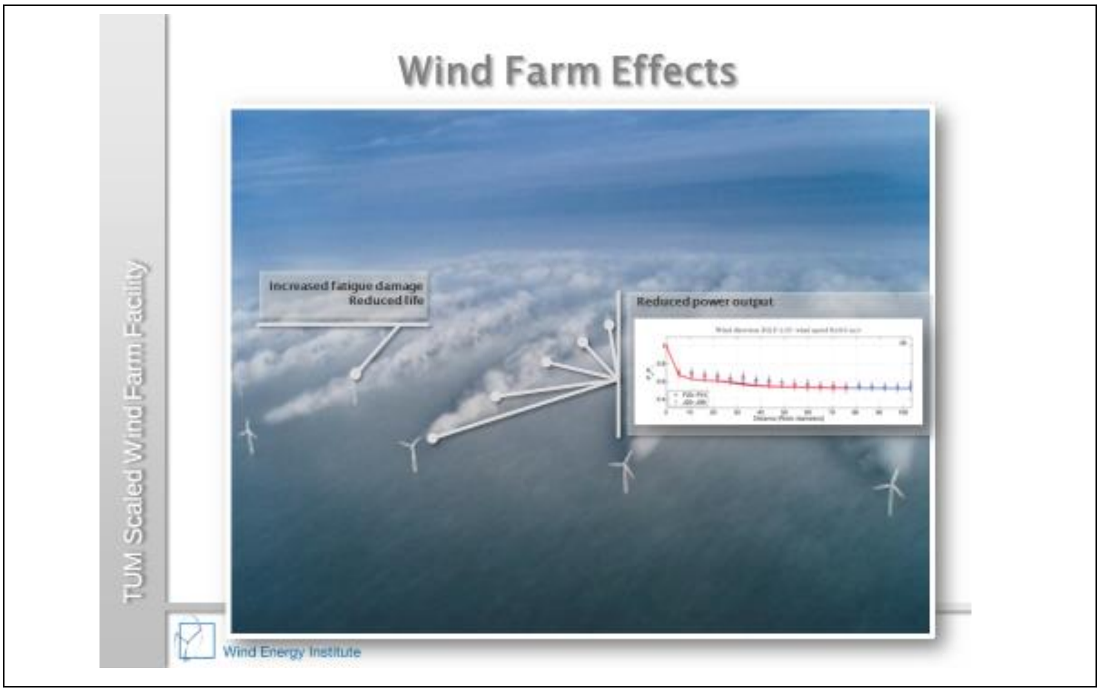
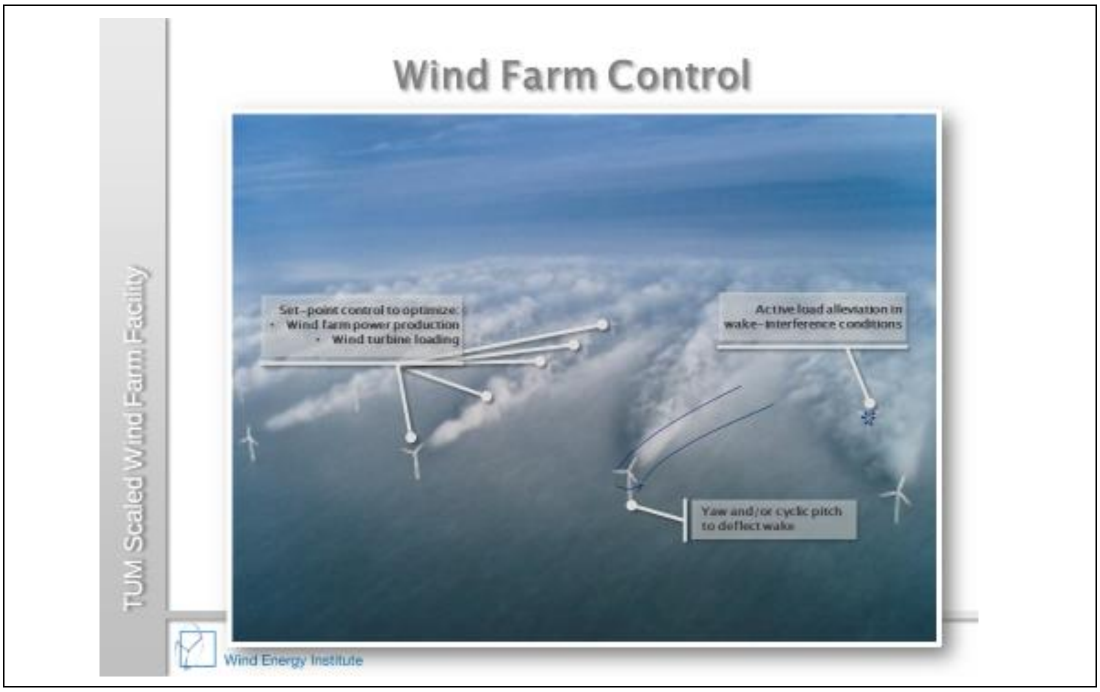
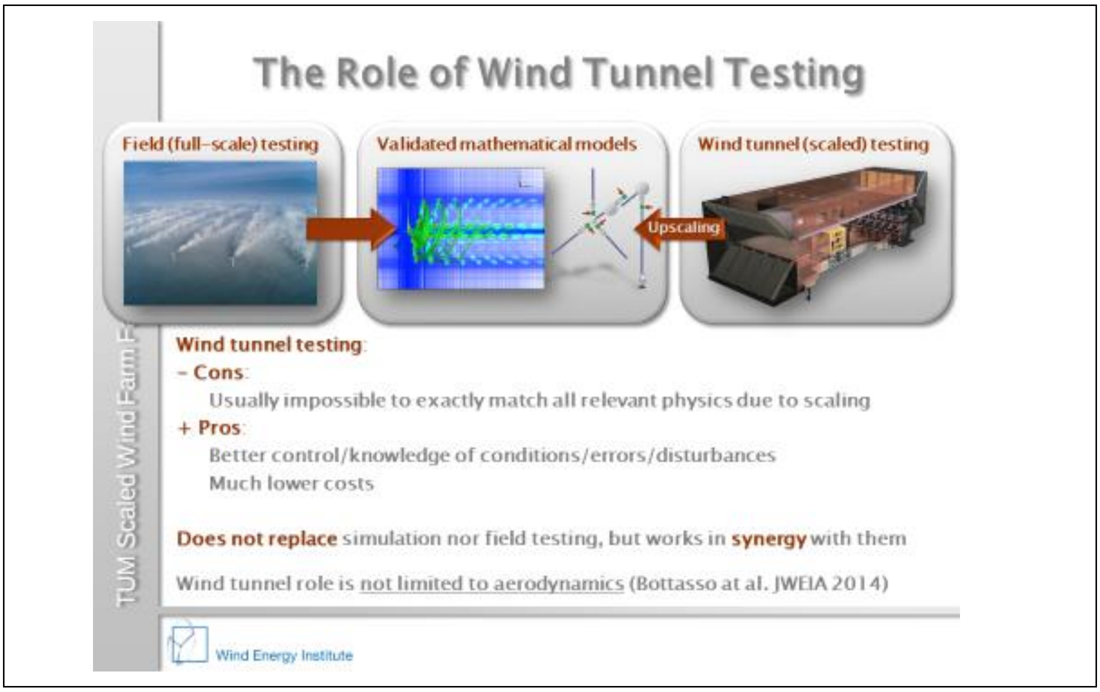
Flow Physics: Wakes and Turbulence

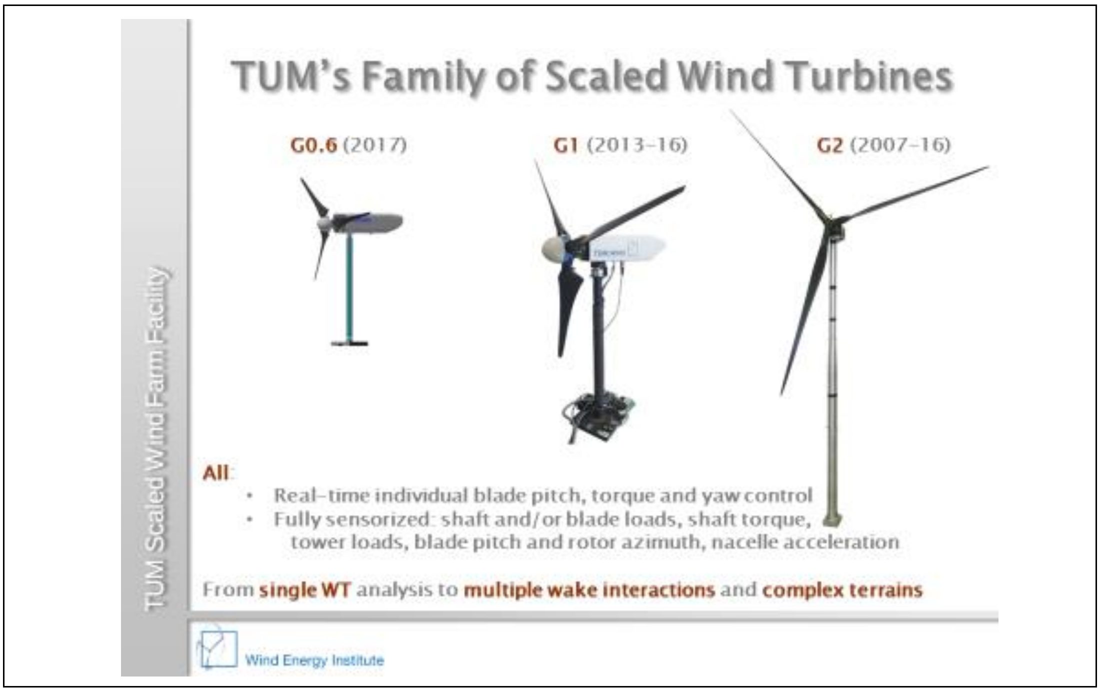


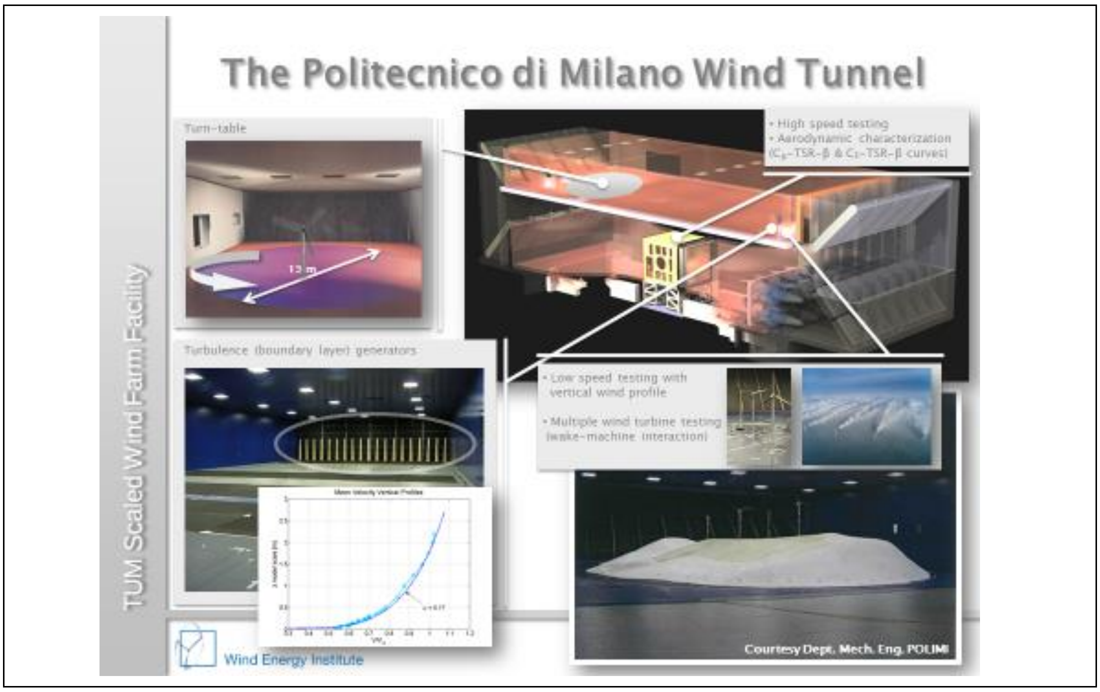
Wind Energy Institute

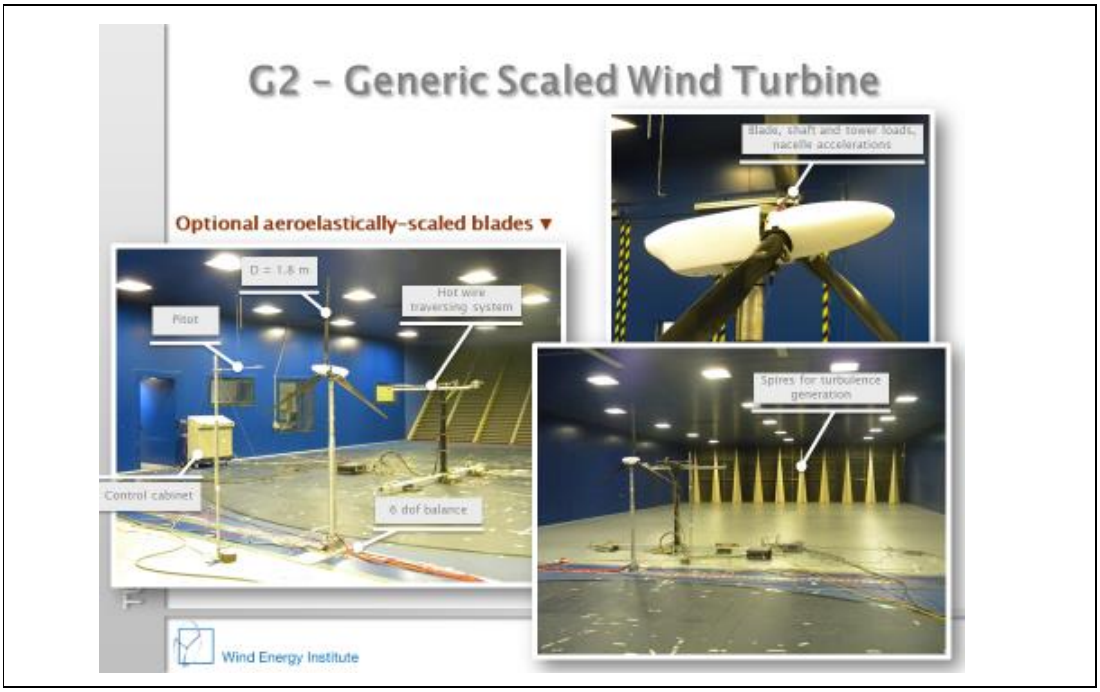

Wind Farm Effects
Increased fatigue damage
Reduced life
Reduced power output
TUM Scaled Wind Farm Facility
Wind Energy Institute

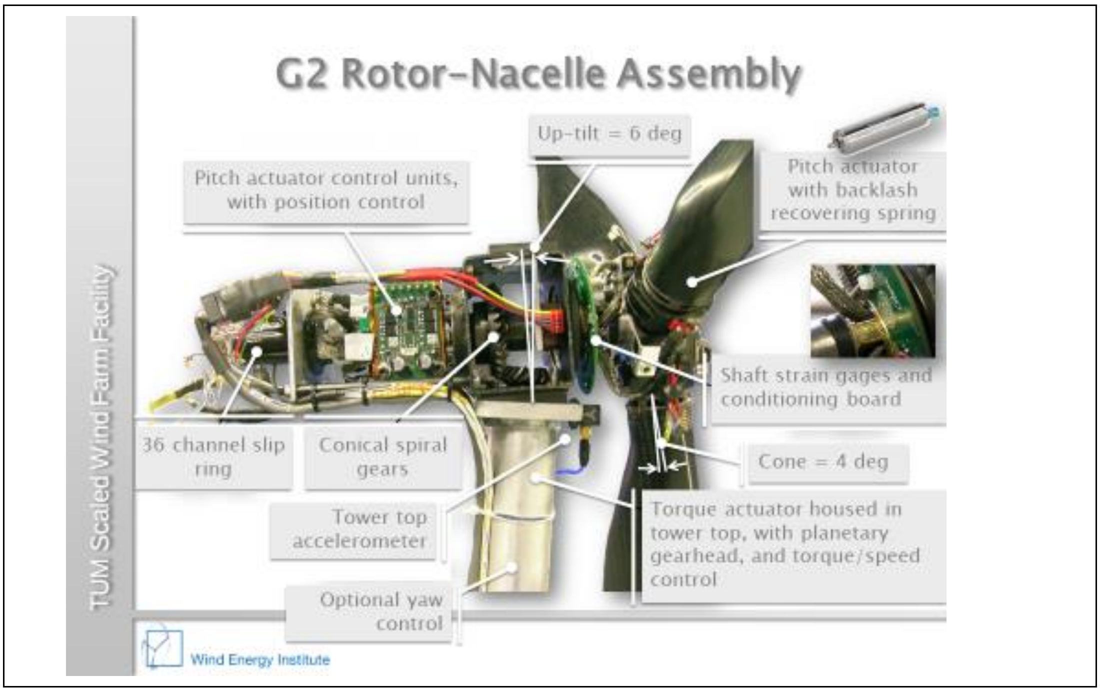

Wind Farm Control
Set-point control to optimize:
• Wind farm power production
• Wind turbine loading
Active load alleviation in
wake-interference conditions
Yaw and/or cyclic pitch
to deflect wake
TUM Scaled Wind Farm Facility
Wind Energy Institute


TUM Scaled Wind Farm F
The Role of Wind Tunnel Testing
Field (full-scale) testing
Validated mathematical models
Wind tunnel (scaled) testing
Upscaling
Wind tunnel testing:
- Cons:
Usually impossible to exactly match all relevant physics due to scaling
+ Pros:
Better control/knowledge of conditions/errors/disturbances
Much lower costs
Does not replace simulation nor field testing, but works in synergy with them
Wind tunnel role is not limited to aerodynamics (Bottasso at al. JWEIA 2014)
Wind Energy Institute

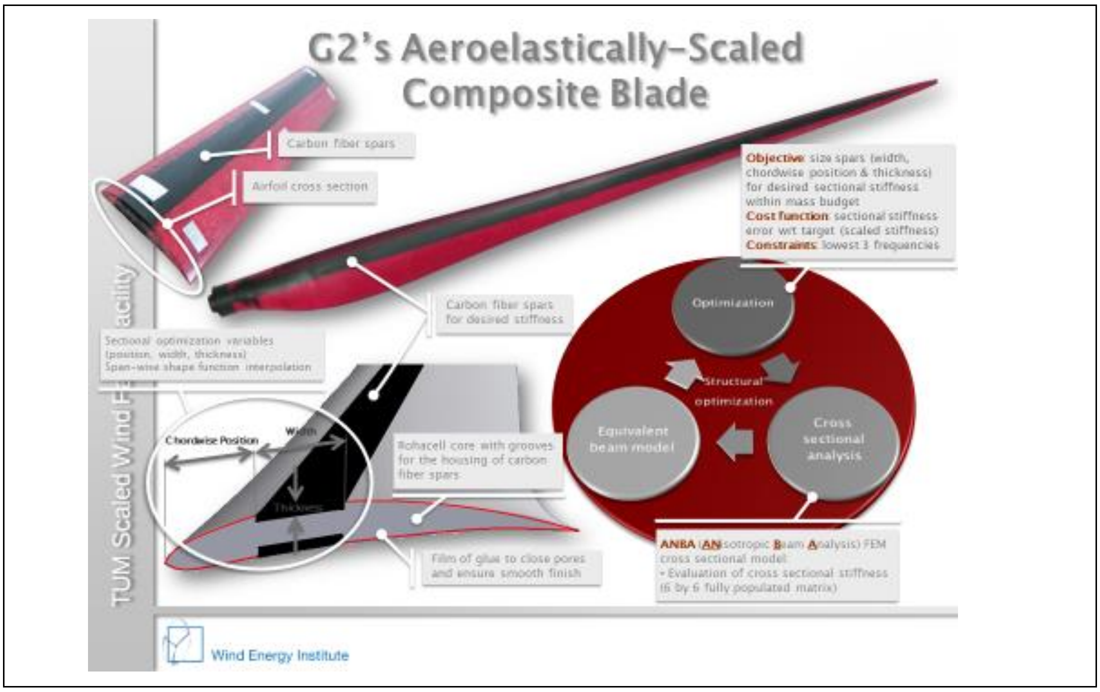

TUM Scaled Wind Farm Facility
TUM's Family of Scaled Wind Turbines
G0.6 (2017)
G1 (2013-16)
G2 (2007-16)
All:
• Real-time individual blade pitch, torque and yaw control
• Fully sensorized: shaft and/or blade loads, shaft torque, tower loads, blade pitch and rotor azimuth, nacelle acceleration
From single WT analysis to multiple wake interactions and complex terrains
Wind Energy Institute


The Politecnico di Milano Wind Tunnel
TUM Scaled Wind Farm Facility
Turn-table
12 m
Turbulence (boundary layer) generators
• High speed testing
• Aerodynamic characterization
• Low speed testing with vertical wind profile
• Multiple wind turbine testing (wake-machine interaction)
Courtesy Dept. Mech. Eng. POLIMI
Wind Energy Institute

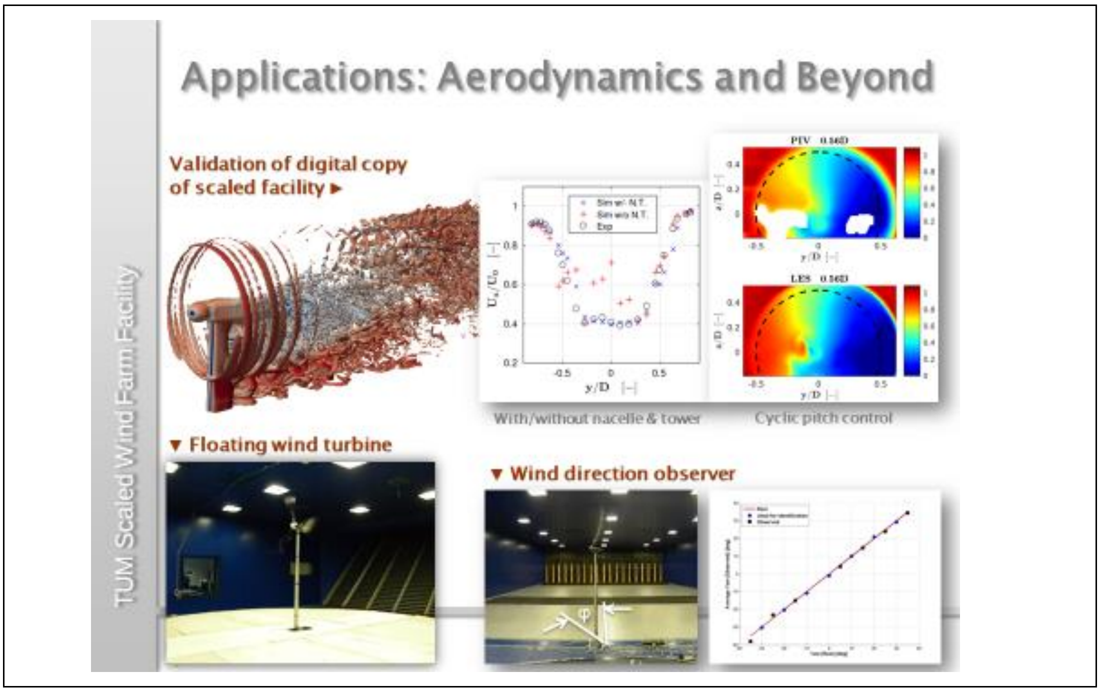

G2 – Generic Scaled Wind Turbine
Optional aeroelastically-scaled blades ▼
D = 1.8 m
Pitot
Hot wire traversing system
Control cabinet
6 dof balance
Blade, shaft and tower loads, nacelle accelerations
Spires for turbulence generation
Wind Energy Institute



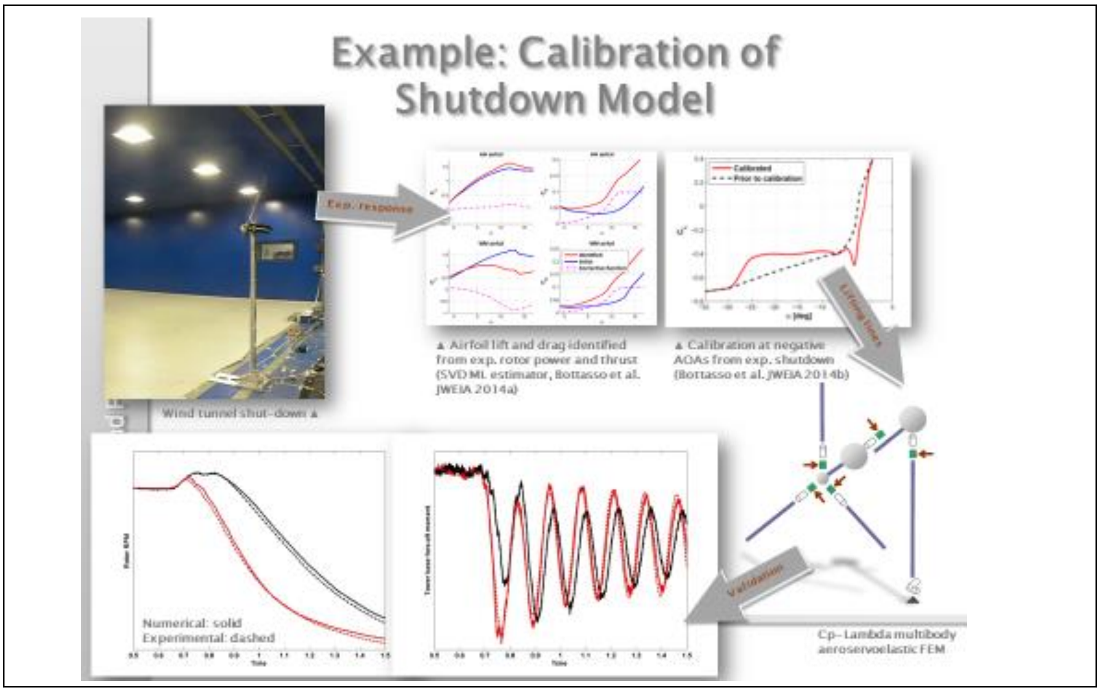
G2 Rotor-Nacelle Assembly
Up-tilt = 6 deg
Pitch actuator control units, with position control
Pitch actuator with backlash recovering spring
Shaft strain gages and conditioning board
36 channel slip ring
Conical spiral gears
Cone = 4 deg
Tower top accelerometer
Torque actuator housed in tower top, with planetary gearhead, and torque/speed control
Optional yaw control
TUM Scaled Wind Farm Facility
Wind Energy Institute

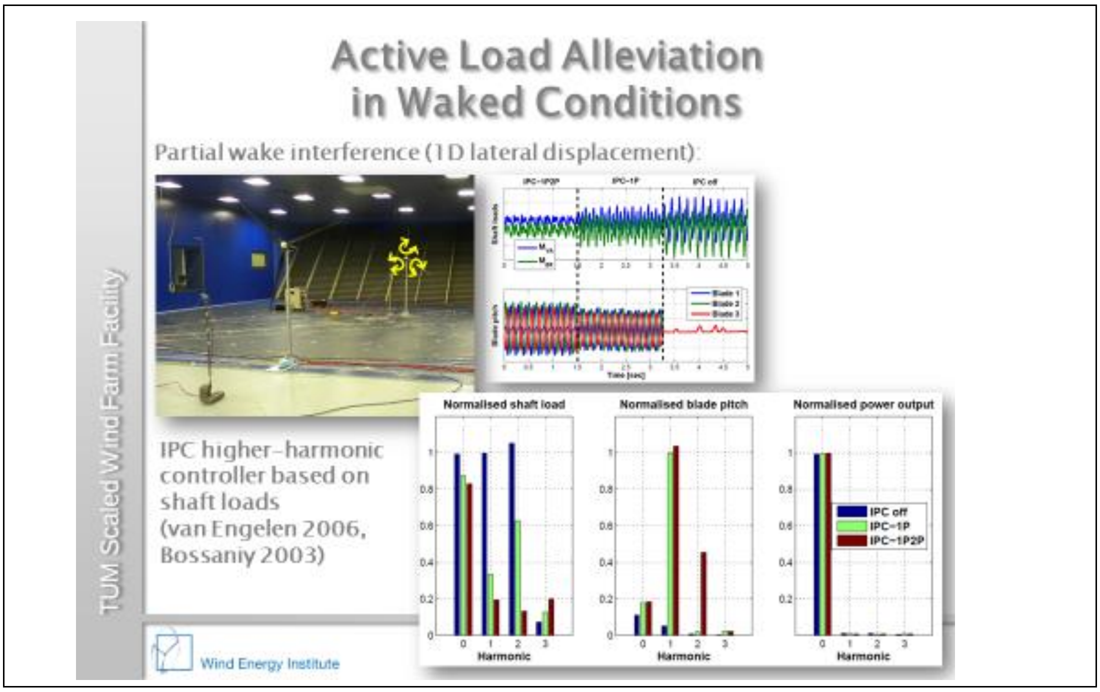


G2's Aeroelastically-Scaled Composite Blade
Carbon fiber spars
Airfoil cross section
Objective: size spars (width, chordwise position & thickness) for desired sectional stiffness within mass budget
Cost function: sectional stiffness error wrt target (scaled stiffness)
Constraints: lowest 3 frequencies
Carbon fiber spars for desired stiffness
Sectional optimization variables (position, width, thickness)
Span-wise shape function interpolation
Optimization
Structural optimization
Equivalent beam model
Cross sectional analysis
Chordwise Position
Width
Thickness
Rohacell core with grooves for the housing of carbon fiber spars
Film of glue to close pores and ensure smooth finish
ANBA (ANisotropic Beam Analysis) FEM cross sectional model
• Evaluation of cross sectional stiffness (6 by 6 fully populated matrix)
Wind Energy Institute



Applications: Aerodynamics and Beyond
TUM Scaled Wind Farm Facility
Validation of digital copy of scaled facility ▸
With/without nacelle & tower
Cyclic pitch control
▾ Floating wind turbine
▾ Wind direction observer


Example: Calibration of Shutdown Model
Exp. response
▲ Airfoil lift and drag identified from exp. rotor power and thrust (SVD ML estimator, Bottasso et al. JWEIA 2014a)
▲ Calibration at negative AOAs from exp. shutdown (Bottasso et al. JWEIA 2014b)
Wind tunnel shut-down ▲
Validation
Numerical: solid
Experimental: dashed
Cp-Lambda multibody aeroservoelastic FEM

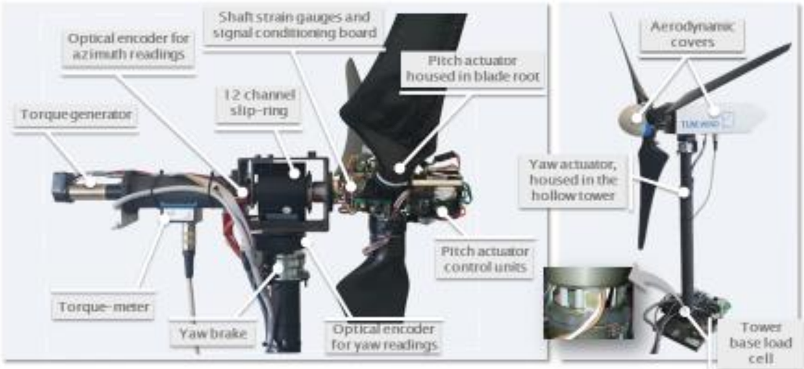


Active Load Alleviation
in Waked Conditions
Partial wake interference (1D lateral displacement):
IPC higher-harmonic
controller based on
shaft loads
(van Engelen 2006,
Bossaniy 2003)
Normalised shaft load
Normalised blade pitch
Normalised power output
IPC off
IPC-1P
IPC-1P2P
Harmonic
Blade 1
Blade 2
Blade 3
TUM Scaled Wind Farm Facility
Wind Energy Institute

Passive & Passive/Active Load Alleviation
in Waked Conditions
Aeroelastically-scaled Bend-Twist Coupled blade:
Partial waked condition ▸
Rigid rotor
BTC rotor
TUM Scaled Wind Farm Facility
Wind Energy Institute

G1 – Generic Scaled Wind Turbine

A smaller machine (1.1 m diameter rotor), to enable complex wind farm scenarios:



TUM Scaled Wind Farm Facility

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TUM Scaled Wind Farm Facility

TUM Scaled Wind Farm Facility

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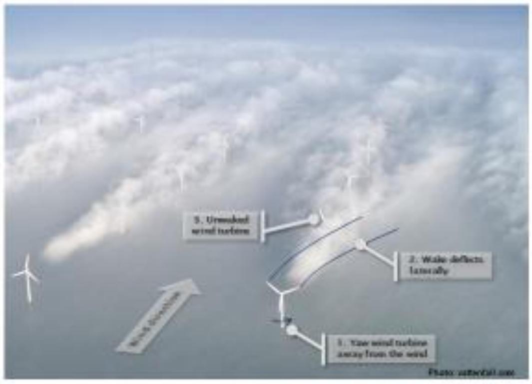
Wake Deflection Wind Farm Control



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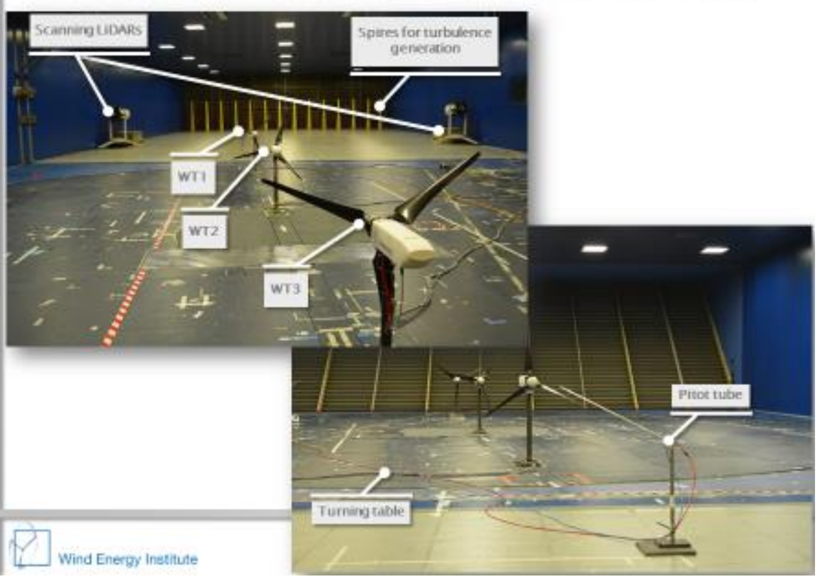
Wake Deflection Wind Farm Control



TUM Scaled Wind Farm Facility

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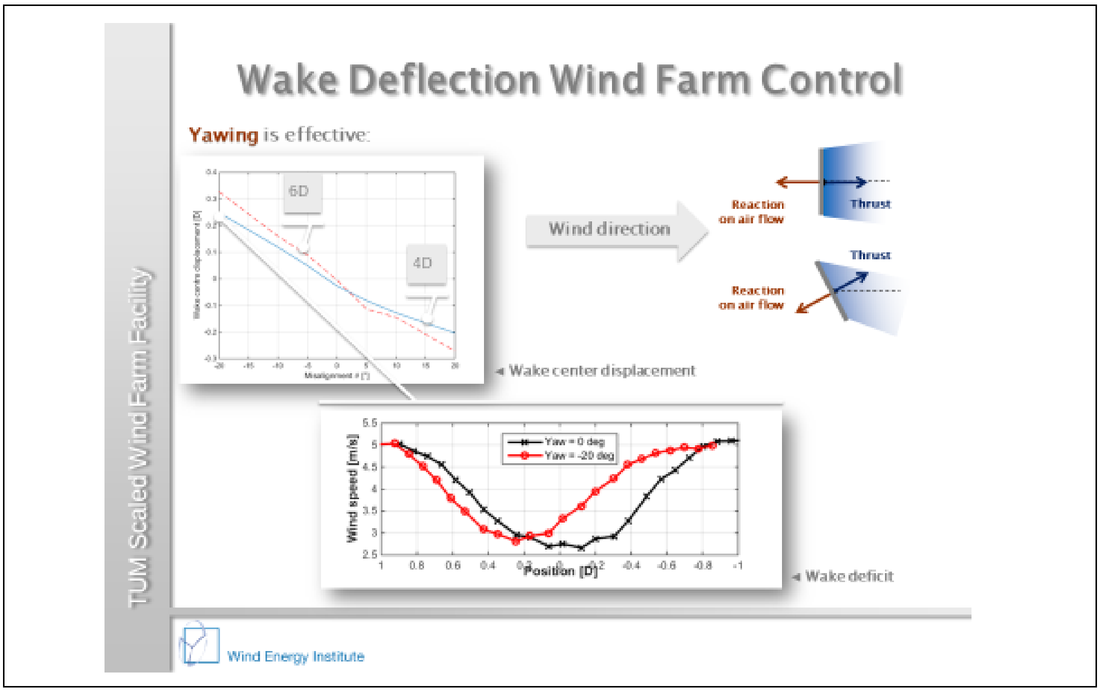
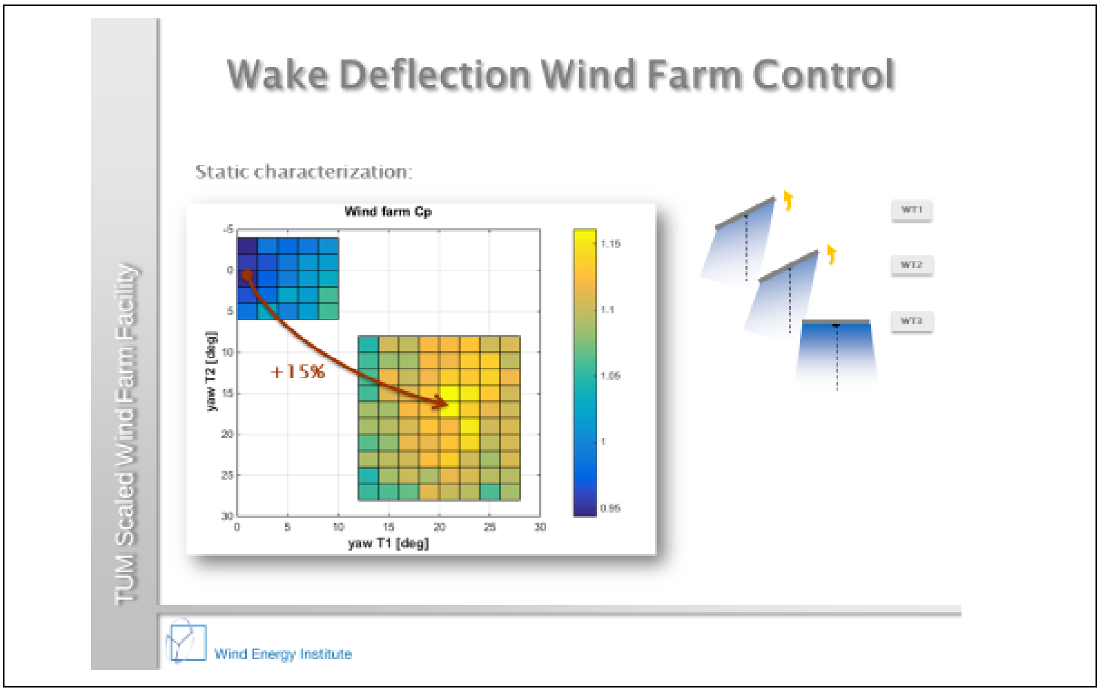
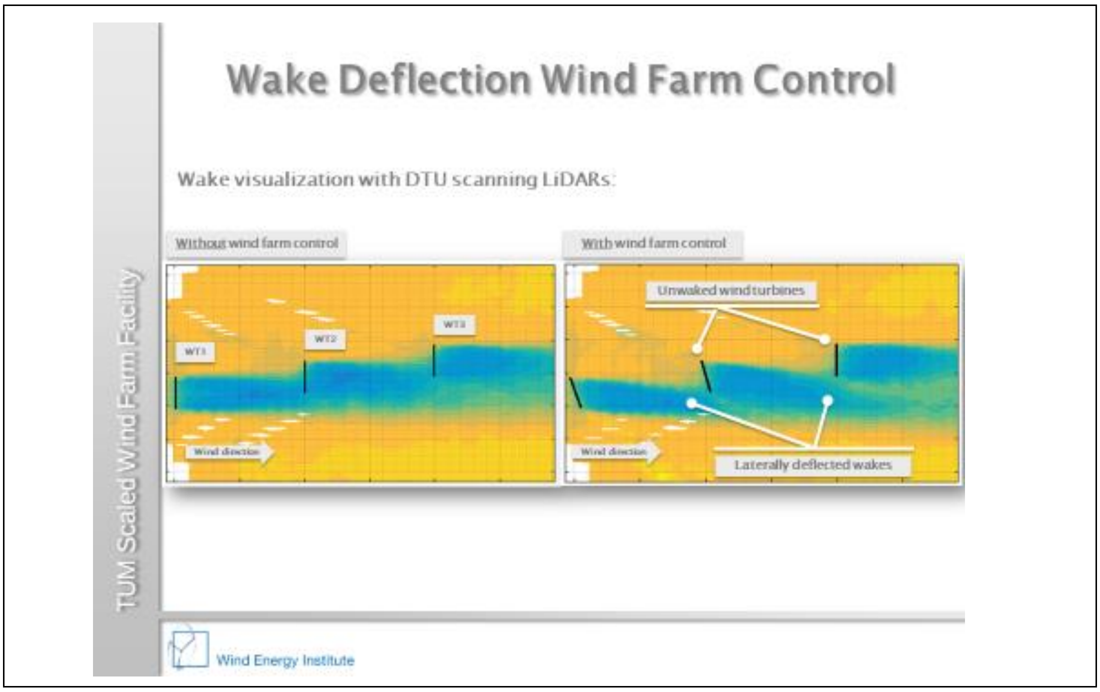
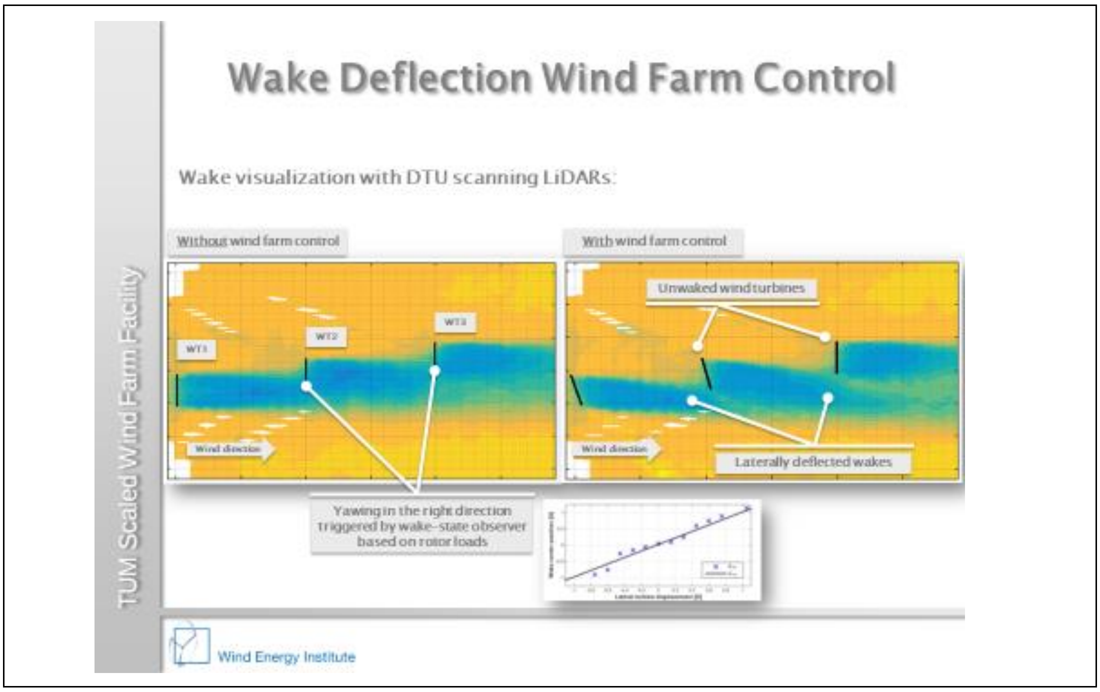
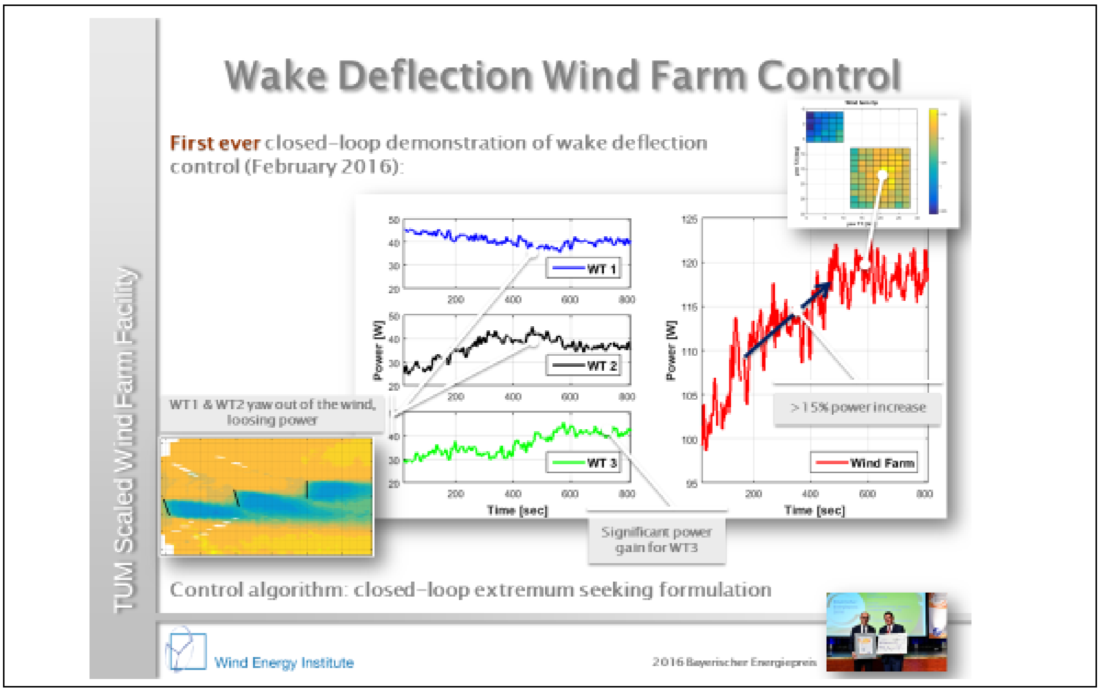
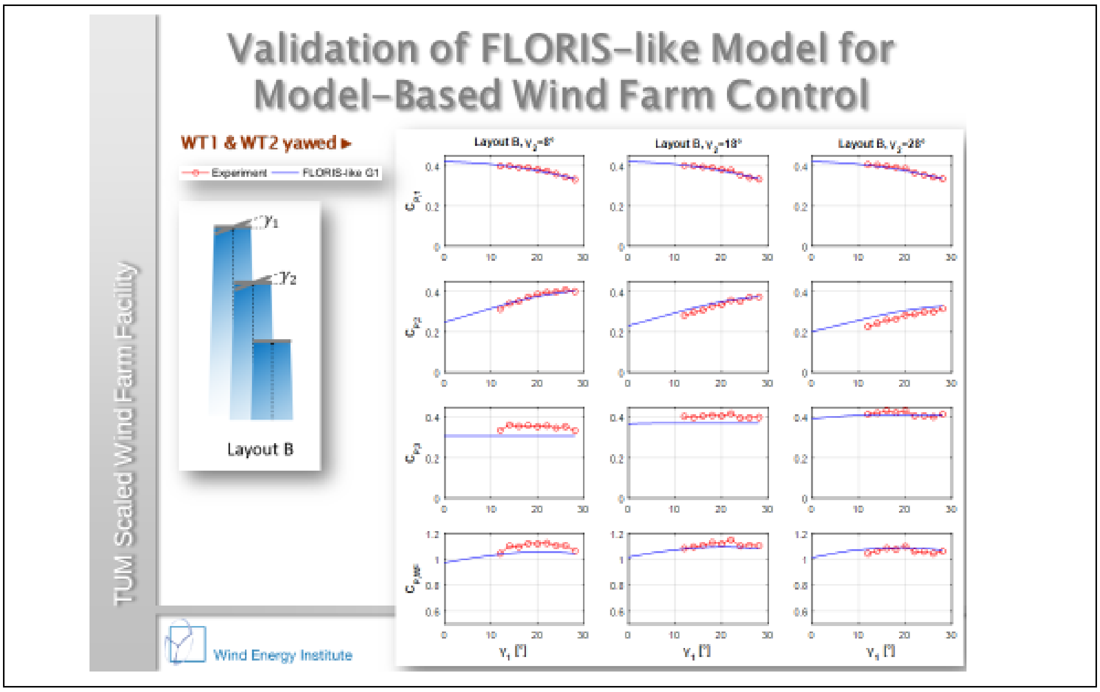

TUM Scaled Wind Farm Facility
Wake Deflection Wind Farm Control
Yawing is effective:
6D
4D
Wind direction
Reaction on air flow
Thrust
Thrust
Reaction on air flow
Wake center displacement
Yaw = 0 deg
Yaw = -20 deg
Wind speed [m/s]
Position [D]
Wake deficit
Wind Energy Institute


TUM Scaled Wind Farm Facility
Wake Deflection Wind Farm Control
Static characterization:
Wind farm Cp
+15%
yaw T2 [deg]
yaw T1 [deg]
WT1
WT2
WT3
Wind Energy Institute


Wake Deflection Wind Farm Control
Wake visualization with DTU scanning LiDARs:
Without wind farm control
With wind farm control
WT1
WT2
WT3
Unwaked wind turbines
Wind direction
Wind direction
Laterally deflected wakes
TUM Scaled Wind Farm Facility
Wind Energy Institute

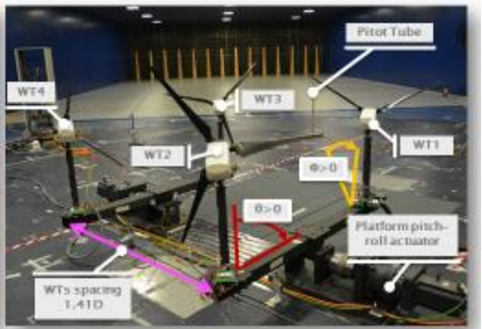

Wake Deflection Wind Farm Control
Wake visualization with DTU scanning LiDARs:
Without wind farm control
With wind farm control
WT1
WT2
WT3
Unwaked wind turbines
Wind direction
Wind direction
Laterally deflected wakes
Yawing in the right direction
triggered by wake-state observer
based on rotor loads
TUM Scaled Wind Farm Facility
Wind Energy Institute


TUM Scaled Wind Farm Facility
Wake Deflection Wind Farm Control
First ever closed-loop demonstration of wake deflection control (February 2016):
WT1 & WT2 yaw out of the wind, loosing power
WT 1
WT 2
WT 3
Power [W]
Time [sec]
Significant power gain for WT3
>15% power increase
Wind Farm
Control algorithm: closed-loop extremum seeking formulation
Wind Energy Institute
2016 Bayerischer Energiepreis


TUM Scaled Wind Farm Facility
Validation of FLORIS-like Model for Model-Based Wind Farm Control
WT1 & WT2 yawed ▸
Experiment
FLORIS-like G1
Layout B
Layout B, γ2=8°
Layout B, γ2=18°
Layout B, γ2=28°
γ1 [°]
Wind Energy Institute

Scaled Wind Farm Facility

Control of Floating Cluster



▲ WWHybrid floating platform concept
KRISO – Korea Research Institute of Ships and Ocean Engineering

▼ Power effect by misalignment (θ=10 deg)

		WT1		WT2		WT3		WT4		WF	
	ϕ	P	ΔP, %	P	ΔP, %	P	ΔP, %	P	ΔP, %	P	ΔP, %
W_s = 4 m/sec	0 deg	12.98	-	4.0	-	12.34	-	3.25	-	32.56	-
	15 deg	11.67	-10.1	6.49	63.1	12.98	5.2	3.34	2.8	34.49	5.9
	25 deg	9.92	-23.6	8.82	121.6	12.87	4.3	3.26	0.2	34.87	7.1
W_s = 5 m/sec	0 deg	23.28	-	11.12	-	23.28	-	8.79	-	66.45	-
	15 deg	22.78	-2.2	13.54	21.8	23.28	0.	9.58	9.0	69.18	4.1
	25 deg	20.5	-12.0	17.38	56.3	23.24	-0.1	8.56	-2.6	69.68	4.8

TUM Scaled Wind Farm Facility

Concluding Remarks

- **Scaled testing** has a role to play:
  - Low cost/risk preliminary test/prioritization of ideas/methods
  - Validation and calibration of models
- We have **significant data sets** that we are willing to **share** with partners:
  - Flow and wake measurements
  - Wind turbine operational data and loads
- We can generate **additional data sets** with relatively little effort and cost, using and/or modifying the existing resources

Next step: **H2020 CL-WINDCON project** (5 MEUR – 3 years):
- New advanced wind farm control methods
- More wind tunnel testing
- Field testing on GE wind turbines

Wind Energy Institute

TUM Scaled Wind Farm Facility

Acknowledgements

Work in collaboration with:
F. Campagnolo, J. Schreiber, E. Nanos, J. Wang, R. Weber, V. Petrović

Work supported in part by:
German Federal Ministry for Economic Affairs and Energy (**BMWi**)
within the **"Compact Wind"** project (FKZ 0325492D)

Other funding from private and public sources in the EU, Korea and USA

Wind Energy Institute

DNV·GL

ENERGY

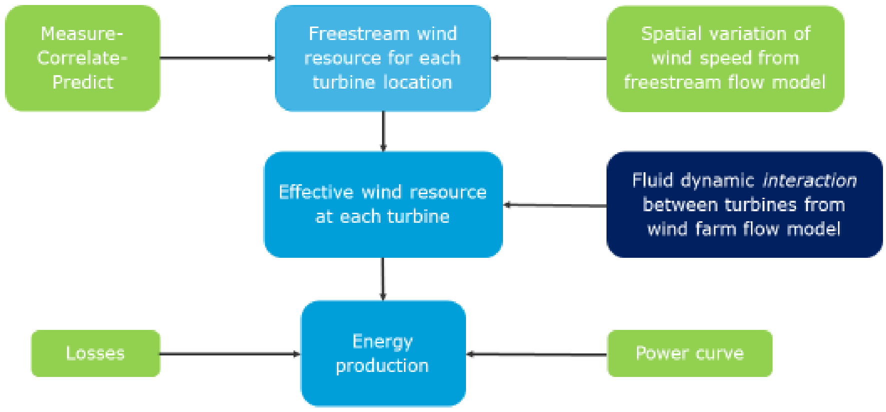
Wind Farm Blockage: Measurement, Prediction, And Impact on Energy Production

James Bleeg, Elizabeth Traiger, Mark Purcell, and Lars Landberg

07 September 2017

SAFER, SMARTER, GREENER

Typical wind energy resource assessment process

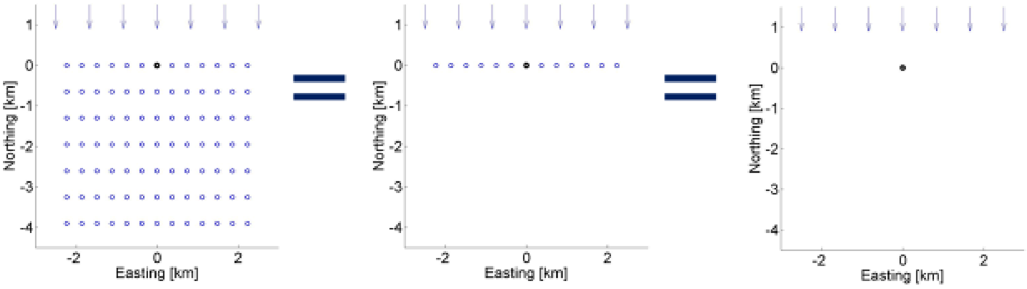


Interaction between wind turbines

The wind industry almost always assumes that turbine interactions are limited to wakes and their impact on turbines downstream—any influence of the turbines on conditions upstream or laterally is ignored.

A fundamental assumption used throughout the industry

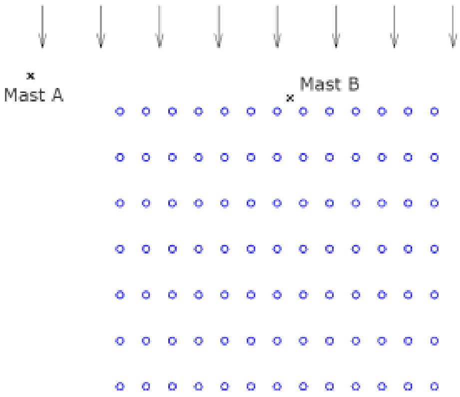
Wind resource assessments assume that the highlighted turbine produces the same amount of energy in each of the three situations below.



We are not aware of any direct evidence substantiating this assumption.

Method

Data analysis approach



Objective: Find out whether and to what degree the wind farm affects the wind speed measured at Mast B

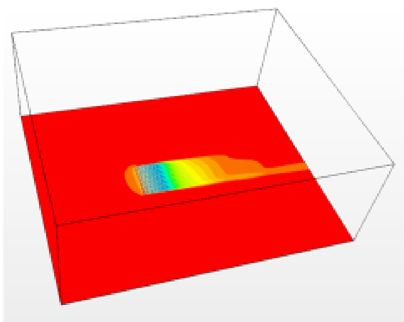
Method (high-level)

- Choose a direction sector where the masts are not waked
- For this sector, determine the wind speed relationship between Mast A and Mast B—before and after the commercial operation date (COD)

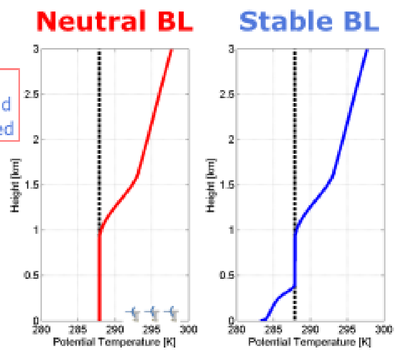
Key Metric: The percent change in the wind speed ratio between Mast A and Mast B, $\Delta U_{B,A}$

DNV GL CFD approach – Solver, domain, and boundary conditions

- STAR-CCM+, steady RANS, k-ε, buoyancy included
- All boundaries, except the ground, are at least 15 km from the wind farm
- At least five inlet directions simulated at each site, clustered around sector of interest
- Neutral BL and stable BL, **with and without turbines**

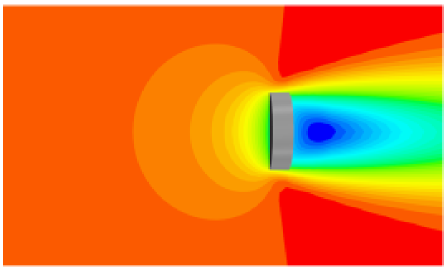


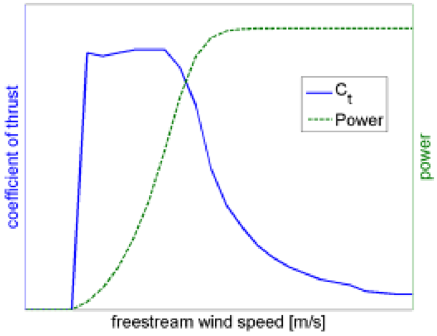
Atmospheric stability within and above BL simulated



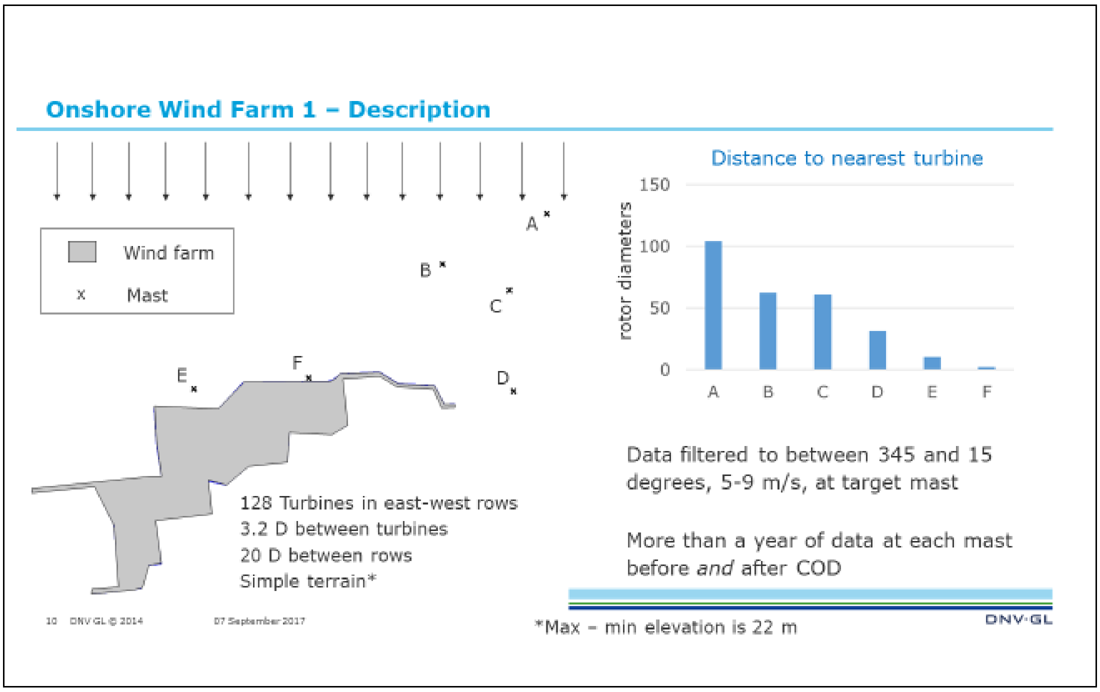
DNV GL CFD approach – Representing the wind turbines

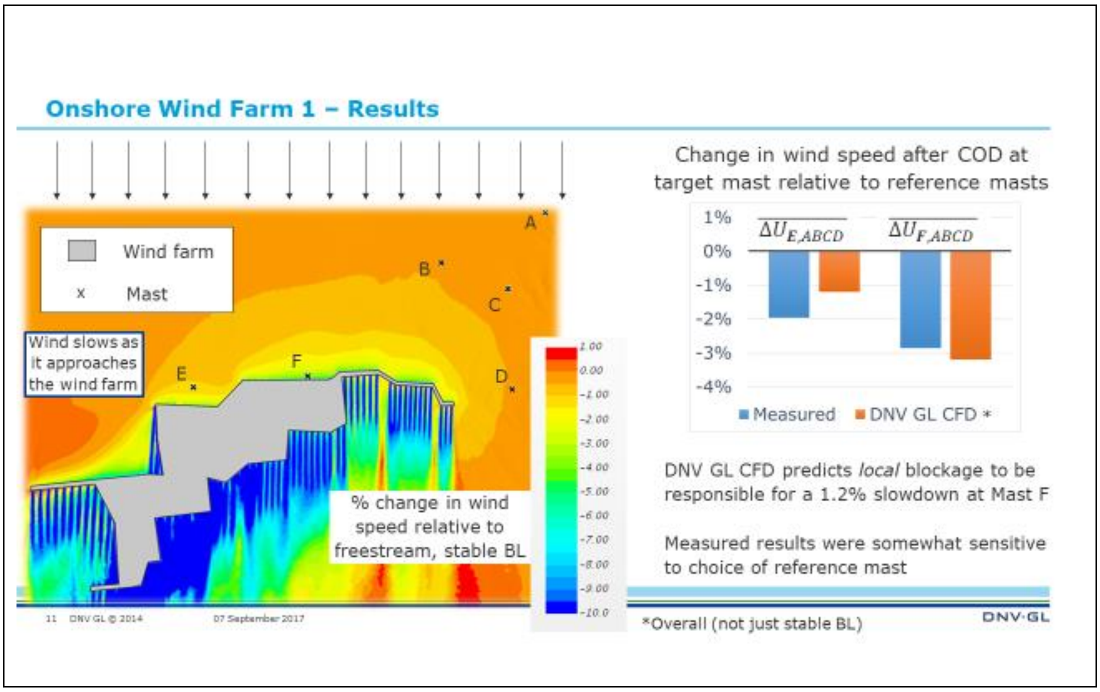
- Wind turbines represented with a simple actuator disk
- Body forces applied based on curves of C_t, power, and rotor speed
- Simulated wind speeds are close to peak C_t, where any blockage effect would be maximized





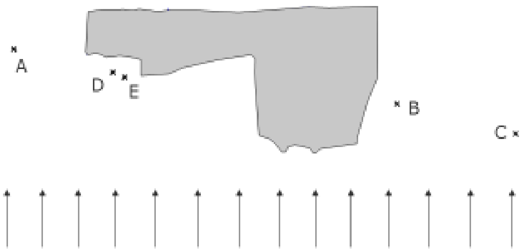
Results

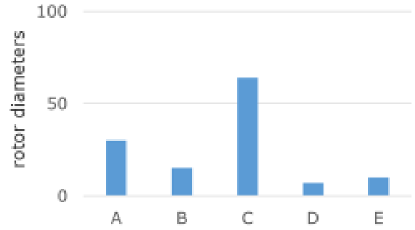

Onshore Wind Farm 1 – Description
Wind farm
Mast
A
B
C
D
E
F
128 Turbines in east-west rows
3.2 D between turbines
20 D between rows
Simple terrain*
Distance to nearest turbine
rotor diameters
150
100
50
0
A B C D E F
Data filtered to between 345 and 15 degrees, 5-9 m/s, at target mast
More than a year of data at each mast before *and* after COD
10 DNV GL © 2014 07 September 2017
*Max – min elevation is 22 m
DNV·GL


Onshore Wind Farm 1 – Results
Wind farm
Mast
Wind slows as it approaches the wind farm
A
B
C
D
E
F
% change in wind speed relative to freestream, stable BL
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.0
Change in wind speed after COD at target mast relative to reference masts
1%
0%
-1%
-2%
-3%
-4%
$\overline{\Delta U_{E,ABCD}}$
$\overline{\Delta U_{F,ABCD}}$
Measured
DNV GL CFD *
DNV GL CFD predicts *local* blockage to be responsible for a 1.2% slowdown at Mast F
Measured results were somewhat sensitive to choice of reference mast
11 DNV GL © 2014 07 September 2017
*Overall (not just stable BL)
DNV·GL

Onshore Wind Farm 2 – Description

>80 Turbines in east-west rows
3.0 D between turbines
10 D between rows
Moderately complex terrain*



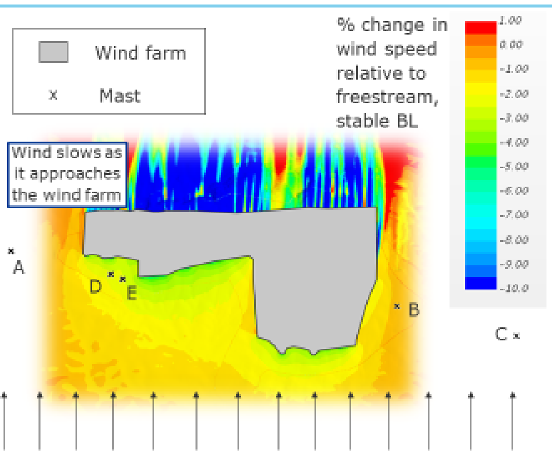


Data filtered to between 165 and 195 degrees and 5-9 m/s, at target mast

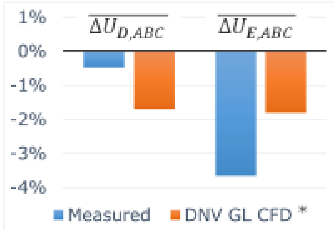
More than a year of data at each mast before *and* after COD

*Max – min elevation is 90 m

Onshore Wind Farm 2 – Results



Change in wind speed after COD at target mast relative to reference masts

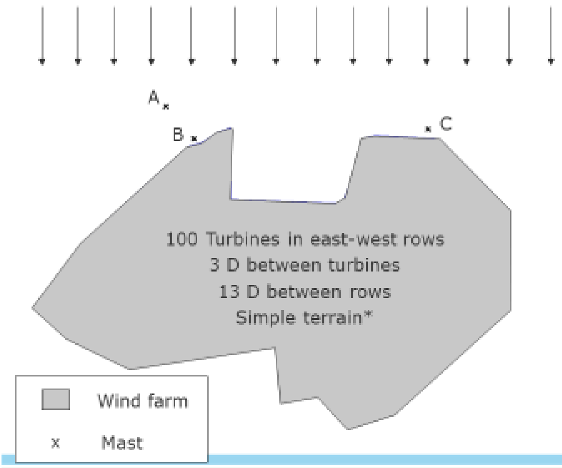


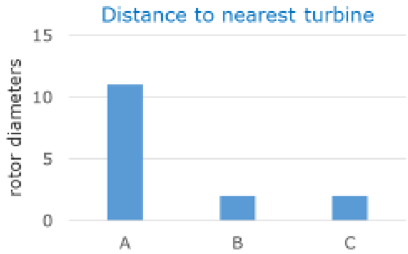
Significant blockage apparent well upstream of the wind farm

Measured results were somewhat sensitive to choice of reference mast

*Overall (not just stable BL)

Onshore Wind Farm 3 – Description



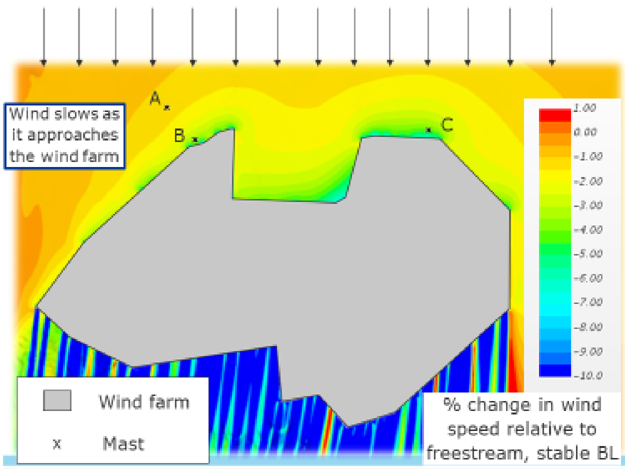


Data filtered to between 345 and 15 degrees, 5-9 m/s, at target mast

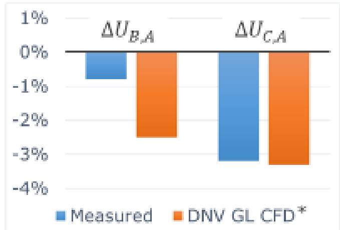
Less than a year of data at each mast before and after COD—5 months post-COD

* Max – min elevation is 21 m

Onshore Wind Farm 3 – Results



Change in wind speed after COD at target mast relative to reference mast



DNV GL CFD predicts the wind speed at Mast A to be 1.3% less than freestream

CFD predicts *local* blockage to be responsible for a 1.2% slowdown at Masts B and C

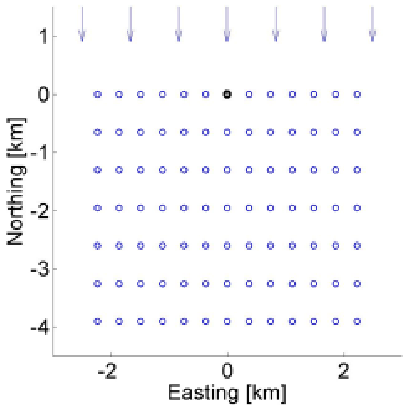
*Overall (not just stable BL)

Summary of results from the four wind farms (two more in backup)

- Wind-farm-scale blockage is consistently evident in the CFD simulations
- Measurements point to a slowdown occurring upstream of each wind farm, implying the presence of wind-farm-scale blockage
- Caution: We are searching for a small signal amid noisy wind data

The implications of wind-farm-scale blockage

The fundamental assumption may be invalid in many cases, resulting in a bias in energy production predictions



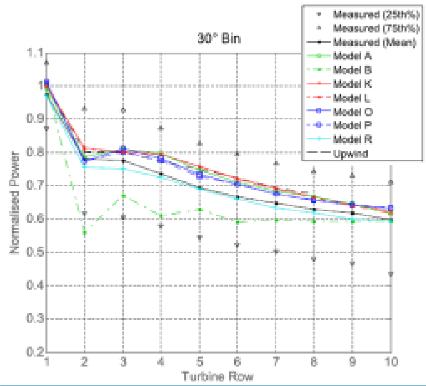
The highlighted turbine is probably not operating in freestream, undisturbed conditions, as is typically assumed

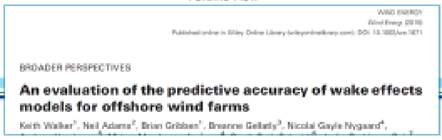
If the wind-farm-scale blockage effect is real…

It is *not* limited to just a re-distribution of energy production along the first row

The sum of the production of the upstream row turbines is very likely to be materially lower than the sum of each of these turbines operating in isolation (i.e. in truly freestream conditions)

A prediction bias related to blockage would not be limited to the first row





BROADER PERSPECTIVES

An evaluation of the predictive accuracy of wake effects models for offshore wind farms

Keith Walker[1], Neil Adams[2], Brian Gribben[1], Breanne Gellatly[3], Nicolai Gayle Nygaard[4],

Current practice in the wind industry:

- Wind farm flow models are used to predict wakes
- The models are tuned to predict the row-by-row *variation* in energy production
- Validations are conducted with energy production *normalized by production in the upstream row*

If blockage causes an upstream row to underproduce by 2%, approaches that ignore blockage will on average overpredict energy production for the ***entire wind farm*** *by the same 2%.*

Blockage and energy impact, a summary

- Observations and CFD results at four projects suggest that wind-farm-scale blockage slows approaching flow to a degree that cannot reasonably be neglected
- Wind-farm-scale blockage *could* represent a material bias in energy assessment procedures used throughout the industry
- The challenge of finding a couple percentage points of signal within noisy data limits to some extent the strength of these conclusions—they are not yet fully proven
- This should be investigated further
  - Dig more into current data sets
  - Obtain more data sets

Opportunity: Accounting for two-way coupling between the atmosphere and the wind farm has the potential to benefit wind farm design, power performance testing, and even wind farm control—further driving down cost of energy

Validating blockage predictions

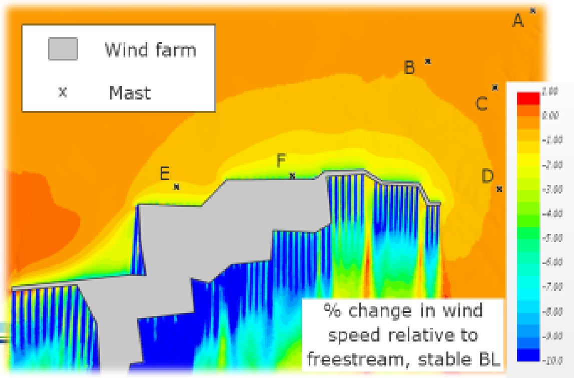
Measuring blockage

- Wind farm flow modelling and measurement campaigns focus on wakes
- All wake prediction tools used in the industry are ultimately validated against full-scale field observations
- Blockage prediction tools will also require validation

- Measurements related to blockage, particularly field measrements, are needed

Measuring blockage (cont.)

- Challenge
  - Not aware of any field measurement campaigns focused on blockage
  - The wind speed changes due to blockage are generally smaller and vary more gradually as compared with wakes, making the blockage impact harder to observe
- Potential sources of useful data
  - Wind tunnel
  - Turbine SCADA data
  - Meteorological masts
  - Scanning lidar (preferably, dual)



Wind tunnel measurements

Wind farm blockage is evident in wind tunnel measurements reported in Ebonach, et al. "A Linearized numerical model of wind-farm flows". *Wind Energy* 2016

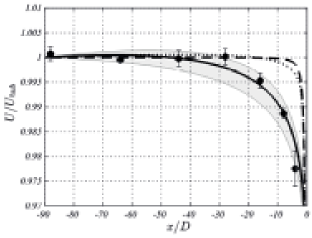


Figure 10. Comparison between wind-farm and single-turbine cases with regard to the upstream blockage effect. The measurement results are represented by (•) with the corresponding standard uncertainty of the mean indicated by error bars. The solid line is the corresponding model prediction (the spatial variation in the spanwise direction is marked by the semi-transparent grey area). The dashed line indicates the single-turbine upstream velocity [31], while the model prediction for the same case is denoted by a dotted line.

Wind tunnel measurements are useful, but not sufficient

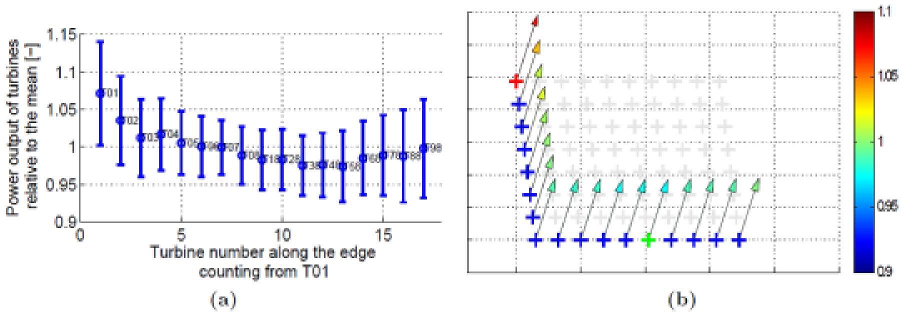
- Lateral and top walls can influence the blockage
- Stratification in the atmosphere is likely an important contributor to blockage
- Will findings scale?

DNV·GL

Turbine SCADA (patterns of production)

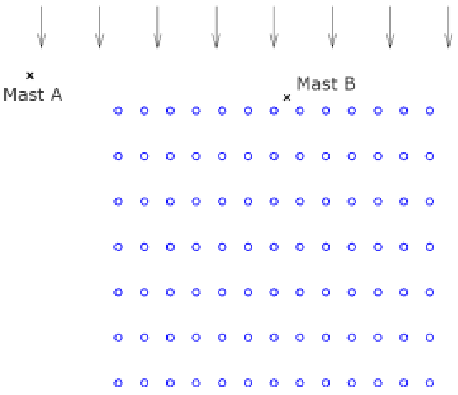
The observed production patterns for unwaked turbines at Horns Rev are consistent with the possible presence of wind-farm-scale blockage.

Insight into the cause is limited and the effect on overall wind farm energy production is unknown. The authors believed the cause to relate to Coriolis and that the wall effects would be "AEP neutral".



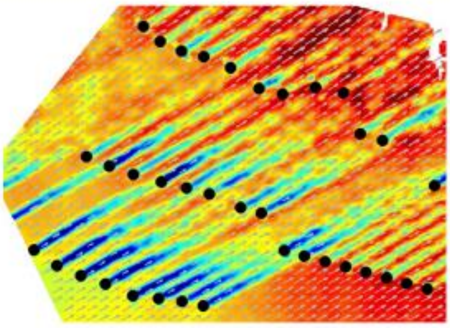
Source: Mitraszewski, et al. "Wall effects in offshore wind farms." Torque 2012

Meteorological masts



- At a given site, we need at least one mast near the perimeter and another mast far from the wind farm, with concurrent measurements before and after COD
- This situation is rare
- Conclusions are limited to the wind speed at a single location (Mast B) relative to another location (Mast A)
- Can be a useful complement to turbine SCADA data and scanning lidar

Scanning lidar or radar (dual scanners would be nice)



http://www.maritimejournal.com/news101/marine-renewable-energy/dual-doppler-radar-project-aims-to-provide-step-change-in-wind-resource-measurement

- Data taken before and after COD needed to account for the spatial variation of mean wind speed *not* caused by the wind farm
- Very useful when combine with multiple upstream masts and turbine SCADA data

Takeaway

- Blockage may need to be accounted for in wind energy assessments
- To do so reliably will require measured data for model validation
- Availability of such data is lacking

Thank you for listening

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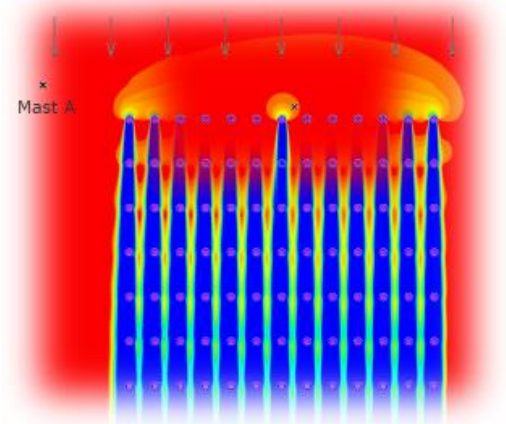
Innovate UK funded a portion of this work through the SWEPT2 project

SAFER, SMARTER, GREENER

Backup

How CFD complements the measured data

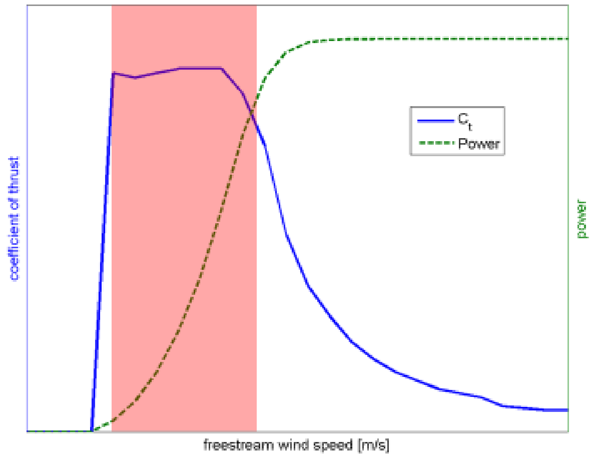


Impact of blockage along the entire upstream row, not just the mast locations

Differentiate between wind-farm-scale blockage and...

local, turbine-scale blockage

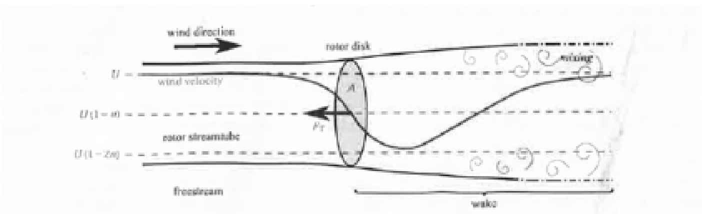
Blockage, C_t, and the power curve



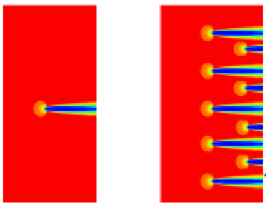
- The blockage effect on wind speed increases with C_t
- Power is very sensitive to wind speed when C_t is high (below rated conditions).

- The impact of blockage on wind farm energy production is potentially large—at least as big as its peak impact on wind speed

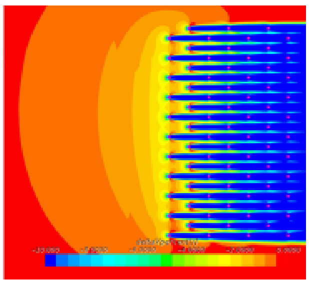
Turbine induction, local blockage, and wind-farm-scale blockage



Wake recovery due to mixing is usually the focus on wind farm flow models



Since the influence of induction is assumed to be largely limited to a distance of 2.5 RD from the rotor, the industry further assumes that induction does not affect neighboring turbines.

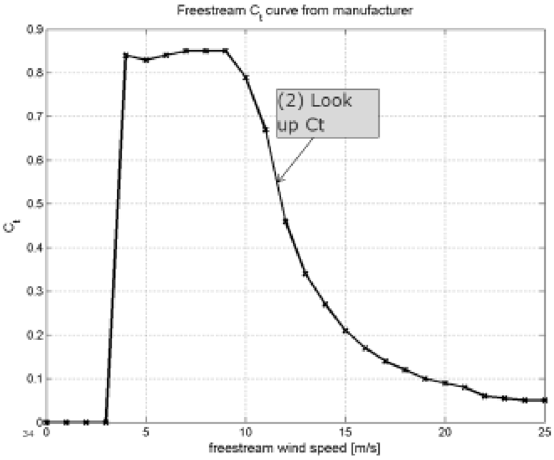


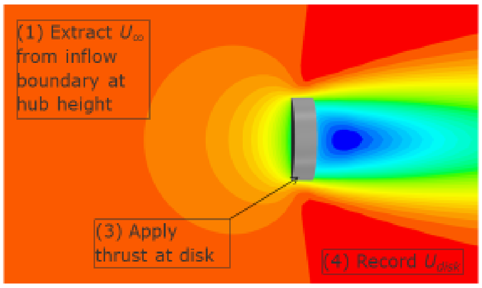
Just a cut-and-paste job representing "mental superposition" of the isolated turbine induction

CFD results suggest a wind-farm-scale blockage

Control of simple actuator disk in CFD – Calibration procedure

Control actuator disk in horizontally-homogeneous flow using regular Ct curve





Record average wind speed over a disk at the turbine location, U_{disk}.

Simulate a range of wind speeds to construct performance curves as functions of U_{disk}.

DNV·GL

MODEL TESTING AND VALIDATION FOR A TLP CONCEPT

Bozonnet Pauline, IFPEN

IEA Wind Task 11, Topical Expert Meeting #88

IFP Energies nouvelles

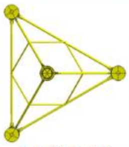
SBM OFFSHORE

INCLINED LEG TLP

Mooring legs are inclined to cross slightly above the nacelle location
➔ Fixed point

Minimal area at the surface
Submerged buoyancy
➔ Decreased wave loads

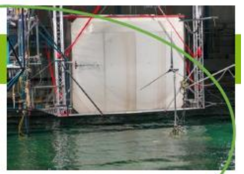
Distributed buoyancy
➔ Stability in towing



Model test

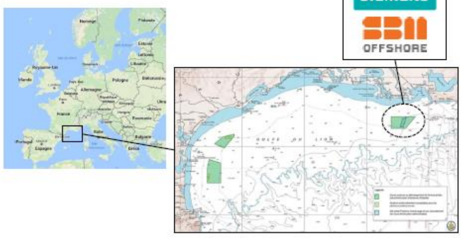
MARIN
3 weeks, summer 2015
5MW design

- *Concept validation*
- *Validation of simulation tools and methodologies*



Provence Grand Large project

Mediterranean sea, 2016 – 2020
Pre-commercial wind farm: 3 x 8 MW



OBJECTIVES

ÉNERGIES NOUVELLES

- Model test campaign to:
  - Get a better understanding of the system – increase maturity
  - Validate and ensure the proper behavior of the concept
    - ➢ Under correct loadings (hydro + aero), motion and acceleration at the nacelle within the expected range (operation + extreme)
    - ➢ No undesired effects in the tensioned system, with a proper downscaling of the main structural modes and rotational frequencies
  - Validate the simulation tools used for design
    - ➢ Step by step methodology

Test Matrix

Characterization tests

- Current, wave, wind calibration
- Fixed wind turbine (onshore)
- Dip and captive tests
- Tests at **60 and 100 m water depth, two floater orientations**:
  - Static load tests
  - Decay tests
  - Hammer test

Design validation tests

  - Current only, wind only, wave only
  - **18 tests** with irregular waves and constant wind: 2 operational and 2 extreme cases

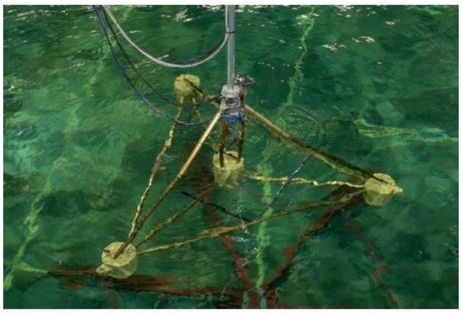
	Wave Hs (m)	Wave Tp (s)	Wave direction (°)	Wind speed (m/s)	Current speed (m/s)
Production	6	10 and 14	0 and 30	26	0
Parked	10	14 and 18	0 and 30	45	0 and 0.5

- Towing tests

ÉNERGIES NOUVELLES

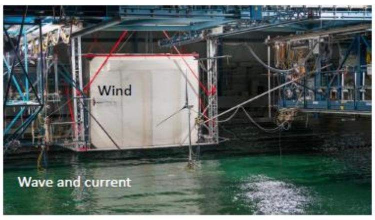
PRESENTATION OUTLINE

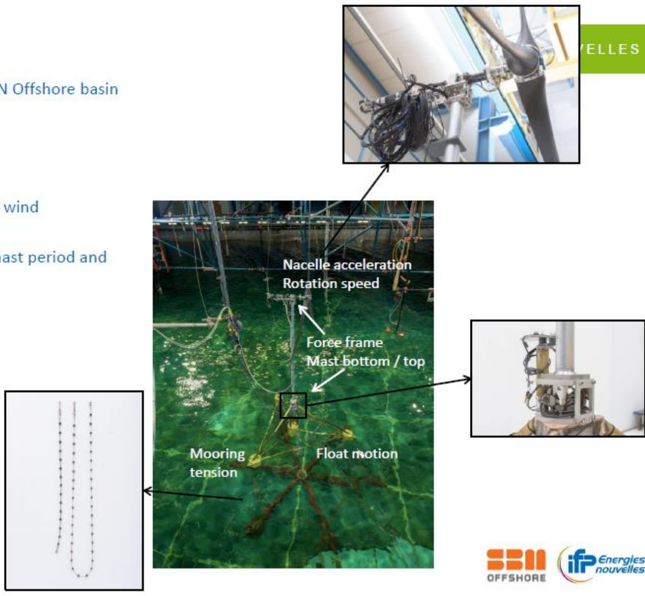
1. Model test campaign
2. Numerical models
3. Hydrodynamic aspects validation
4. Aerodynamic aspects validation
5. Wind and wave tests comparison with simulations



1. MODEL TEST CAMPAIGN

- 3 weeks in August / September 2015, at MARIN Offshore basin
- Floater design for a 5 MW wind turbine
- Measurements
- Downscaling based on Froude similitude:
  - Environmental loads: waves, current and wind
  - Proper hydro. behavior
  - Structural aspects: rigid floater, proper mast period and mooring line axial stiffness

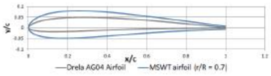


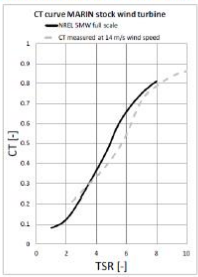


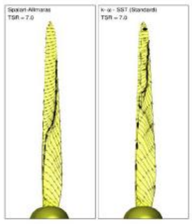
MODEL TEST CAMPAIGN – AERO ASPECTS (1)

ÉNERG

- Problematic: Froude's similitude does not maintain Reynolds number
- Use of the Marin Stock Wind Turbine (MSWT), mimics the NREL 5MW at scale 1/50:
  - Low-Reynolds airfoils







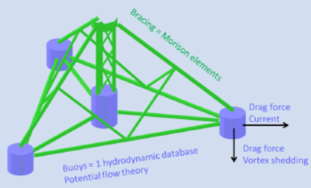
(a) Spalart-Allmaras (b) $k-\omega$ SST

- Aerodynamic effects specific to basin scale
  - Need for calibration / correction of polar curves

References :
de Ridder, Erik-Jan, et al. "Development of a Scaled-Down Floating Wind Turbine for Offshore Basin Testing." *ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*. ASME, 2014.
Kimball, Richard, et al. "Wind/wave basin verification of a performance-matched scale-model wind turbine on a floating offshore wind turbine platform." *ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*. ASME, 2014.
Make, M., & Vaz, G. (2015). Analyzing scaling effects on offshore wind turbines using CFD. Renewable Energy, 83, 1326-1340.

2. NUMERICAL MODELS

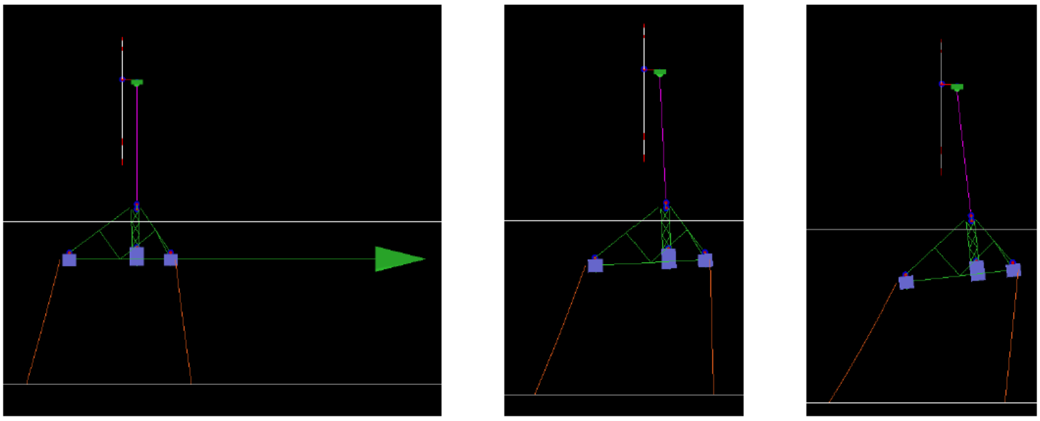
ÉNERGIES NOUVELLES

Tools	Orcaflex	DeepLinesWind
Type of simulation	**Hydro-elastic** **Simply Coupled Simulations - SCS**	**Aero-servo-hydro-elastic** **Fully Coupled Simulations - FCS**
Aerodynamic and control	**Imposed** aerodynamic loading 6-component tensor measured at tower top	**Computed** aerodynamic loading BEM theory + corrections for secondary effects PID controller – 1 constant rotational speed
Simulation scale	Exact reproduction of basin loadings (model scale) at full scale	
Hydrodynamic model	Buoys : Diffraction-radiation Bracing: Morison elements a priori calibration based on: - DNV RP C205 - CFD - SBM REX on CALM Buoys 1st order Airy waves, Wheeler stretching	
Structural model	Rigid float Finite elements for mooring, tower, blades	

3. HYDRODYNAMIC ASPECTS VALIDATION (1)

ÉNERGIES NOUVELLES

- Static load test



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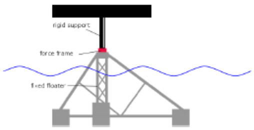
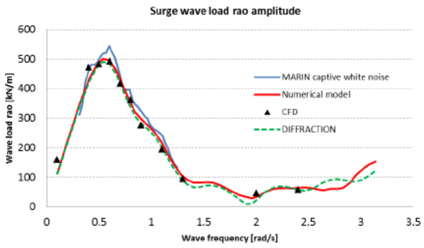
3. HYDRODYNAMIC ASPECTS VALIDATION (2)

ÉNERGIES NOUVELLES

- Wave load RAOs





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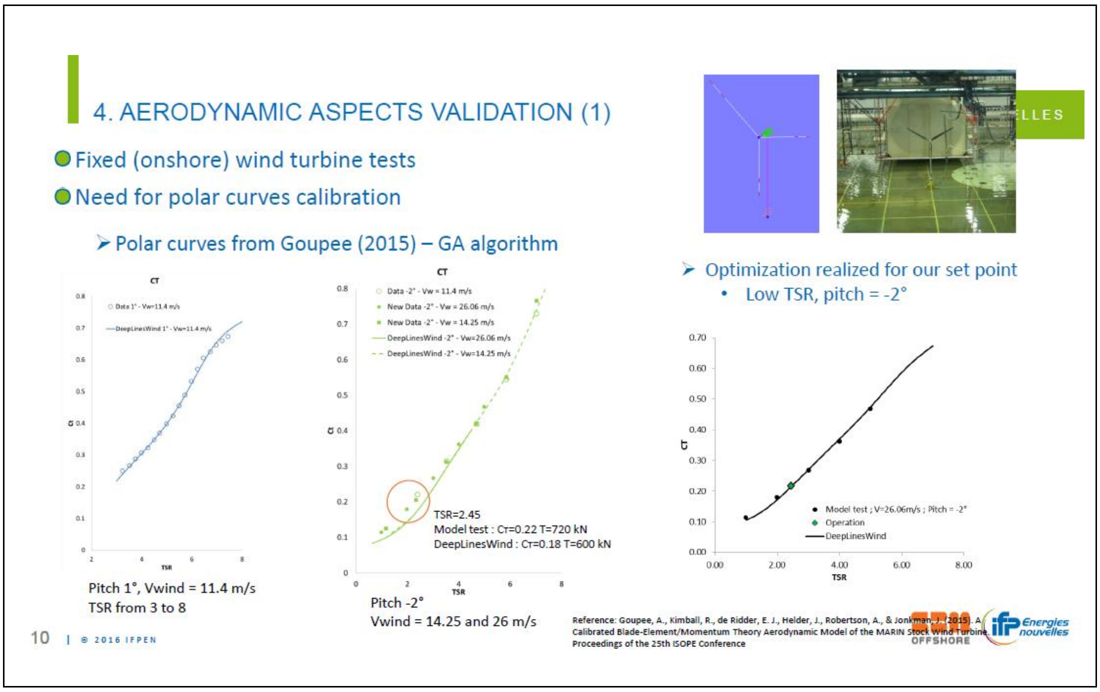
4. AERODYNAMIC ASPECTS VALIDATION (1)
Fixed (onshore) wind turbine tests
Need for polar curves calibration
Polar curves from Goupee (2015) – GA algorithm
Optimization realized for our set point
Low TSR, pitch = -2°
TSR=2.45
Model test : CT=0.22 T=720 kN
DeepLinesWind : CT=0.18 T=600 kN
Model test ; V=26.06m/s ; Pitch = -2°
Operation
DeepLinesWind
Pitch 1°, Vwind = 11.4 m/s
TSR from 3 to 8
Pitch -2°
Vwind = 14.25 and 26 m/s
Reference: Goupee, A., Kimball, R., de Ridder, E. J., Helder, J., Robertson, A., & Jonkman, J. (2015). A Calibrated Blade-Element/Momentum Theory Aerodynamic Model of the MARIN Stock Wind Turbine. Proceedings of the 25th ISOPE Conference
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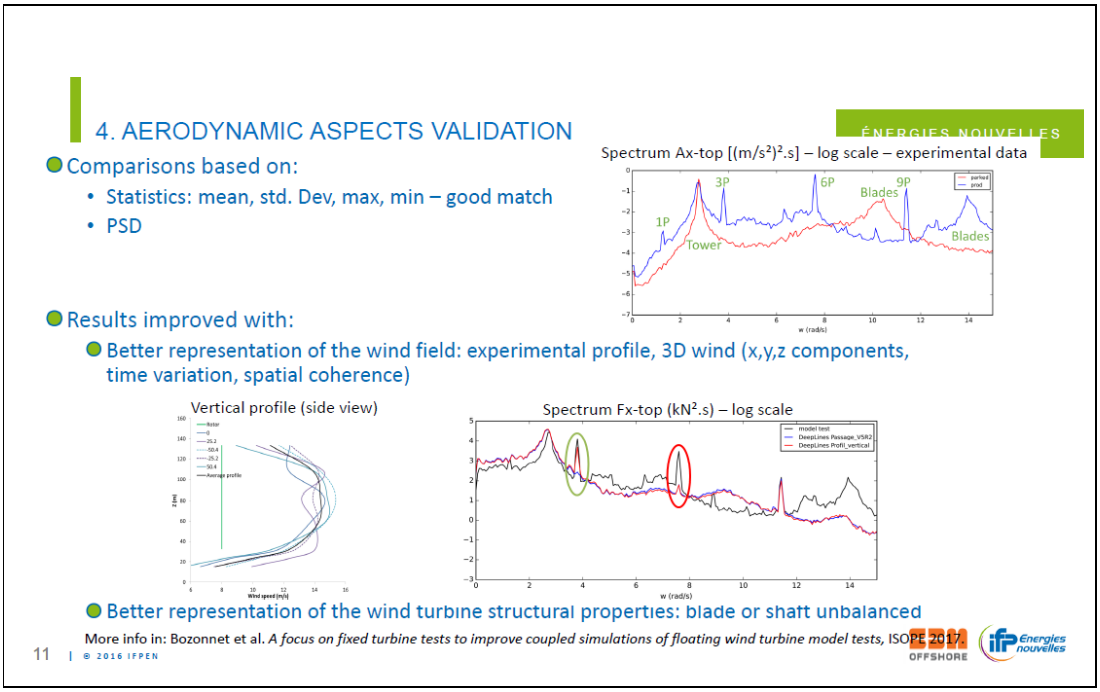
4. AERODYNAMIC ASPECTS VALIDATION
ÉNERGIES NOUVELLES
Comparisons based on:
Statistics: mean, std. Dev, max, min – good match
PSD
Spectrum Ax-top [(m/s²)².s] – log scale – experimental data
1P
3P
6P
9P
Tower
Blades
Blades
Results improved with:
Better representation of the wind field: experimental profile, 3D wind (x,y,z components, time variation, spatial coherence)
Vertical profile (side view)
Spectrum Fx-top (kN².s) – log scale
Better representation of the wind turbine structural properties: blade or shaft unbalanced
More info in: Bozonnet et al. A focus on fixed turbine tests to improve coupled simulations of floating wind turbine model tests, ISOPE 2017.
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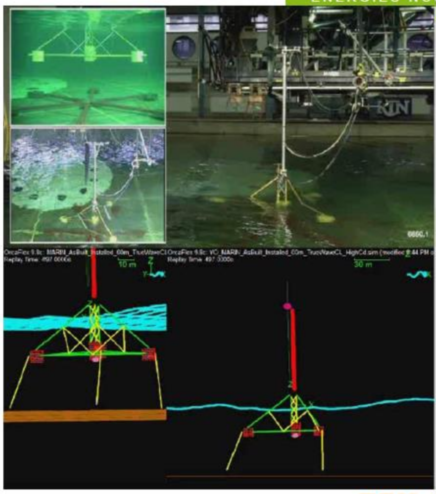
5. COUPLED SIMULATIONS

ÉNERGIES NOUVELLES

- Parked case:
  - Hs=9m, Tp=14s, γ=1.3
  - Uwind=44m/s
  - No current
  - Co-linear wind and wave



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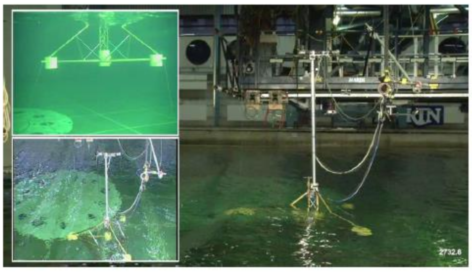
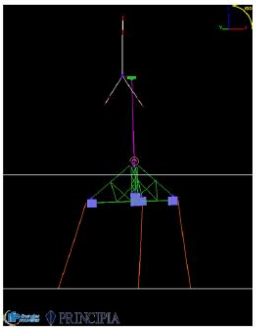
5. COUPLED SIMULATIONS

ÉNERGIES NOUVELLES

- Extreme production case:
  - Hs=6m, Tp=10s, γ=1.3
  - Uwind=26m/s
  - No current
  - Co-linear wind and wave





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CONCLUSIONS AND PERSPECTIVES

ÉNERGIES NOUVELLES

Campaign achievements:

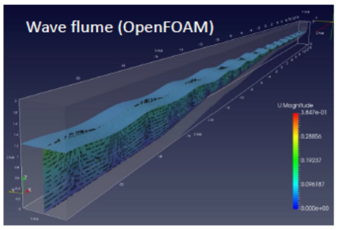
- Floater behavior as expected in towing, production and parked modes
- Ability of the numerical models to forecast the system performances is confirmed, based on a step-by-step methodology:
  - Aero: good agreement on the mean values and on modes location. Difficulties encountered regarding the mode intensity.
  - Wind and wave tests:
    - Good agreement with the SCS simulations
    - FCS simulations show the same discrepancies as for the fixed wind turbine tests

CONCLUSIONS AND PERSPECTIVES

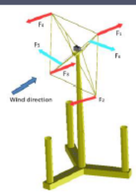
ÉNERGIES NOUVELLES

Perspectives:

- Discrepancies remain for the FCS, coming from the aerodynamic modelisation:
  - Limited knowledge of wind turbine model (1P,6P) and wind field (general level of spectra) in wave basin
  - Aerodynamic phenomena specific to the model scale:
    - Low Reynolds, spanwise flow (intresic to MSWT)
    - High angle of attacks (scale 1/50 to 1/40)
    - Tests with new polar curves (from 3D CFD)
    - Simulations with lifting line theory instead of BEM theory



- Alternatives
  - Numerical wave tank to investigate precise hydro. problematics
  - Hybrid model tests
  - REX on in-situ data
- Extrapolation: model scale to full scale



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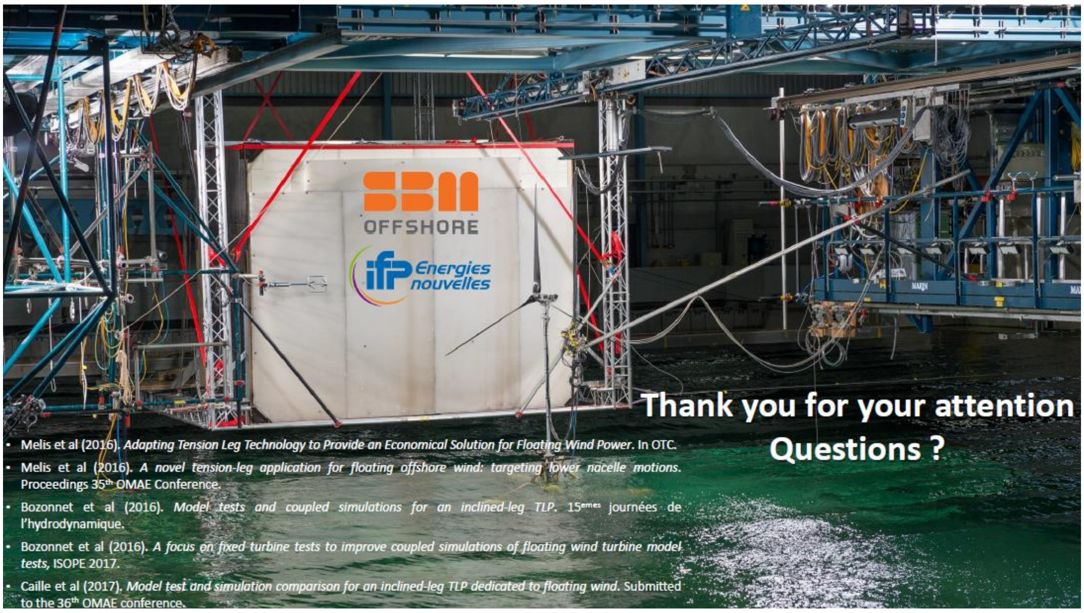
Bayati et al. (2013). Wind tunnel tests on floating offshore wind turbines: A proposal for hardware-in-the-loop approach to validate numerical codes. *Wind Engineering, 37.*



- Melis et al (2016). *Adapting Tension Leg Technology to Provide an Economical Solution for Floating Wind Power.* In OTC.
- Melis et al (2016). *A novel tension-leg application for floating offshore wind: targeting lower nacelle motions.* Proceedings 35th OMAE Conference.
- Bozonnet et al (2016). *Model tests and coupled simulations for an inclined-leg TLP.* 15èmes journées de l'hydrodynamique.
- Bozonnet et al (2016). *A focus on fixed turbine tests to improve coupled simulations of floating wind turbine model tests,* ISOPE 2017.
- Caille et al (2017). *Model test and simulation comparison for an inclined-leg TLP dedicated to floating wind.* Submitted to the 36th OMAE conference.

Continuous Verification and Validation of an In-house Software for Wind Turbine Load Calculation

Philipp Thomas

IEA Wind task 11 | Topical Expert Meeting #88
Edinburgh, Scotland
6th-8th of September, 2017

 1 / 14 Fraunhofer IWES

Fraunhofer IWES

Staff: 160 employees
Located in: Bremerhaven, Bremen, Oldenburg, Hanover

Applied Research
- Site assessments, CFD, wind farm modelling & simulation, accredited field measurements of operating turbines
- Rotor: aerodynamic modelling, qualification of composite materials & components, industrialized manufacturing
- Drive train & grid connection
- Foundations, assessment of soil conditions & geotechnics

Testing Facilities
- Rotor blade test hall
- DyNaLab
- Support structure test center
- 8 MW research wind turbine

Source: www.wind-turbine-models.com

Offshore Wind Turbine System Model Development at IWES

Fields of research
- New concepts for floating offshore foundations
- State-of-the-art modeling of ice-structure interaction
- Reliable and validated coupled system modeling
- Design and control optimization

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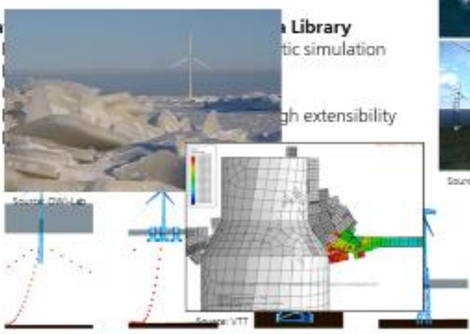

Validation of Simulation Tools – Motivation

Tools must continuously be verified and validated due to
- Importance of the simulated loads (design, certification)
- New challenges for tools / new features of tools

Objectives for validation activities
- Assess simulation accuracy and reliability
- Investigate capabilities of implemented theories
- Refine applied analysis methods
- Identify further R&D needs

Verification & Validation of IWES in-house OWT simulation tool
- Verification against GH Bladed and NREL FAST
- IEA OC5 project → Validation against measurement data
- Smart Blades 2 project → Validation against measurement data

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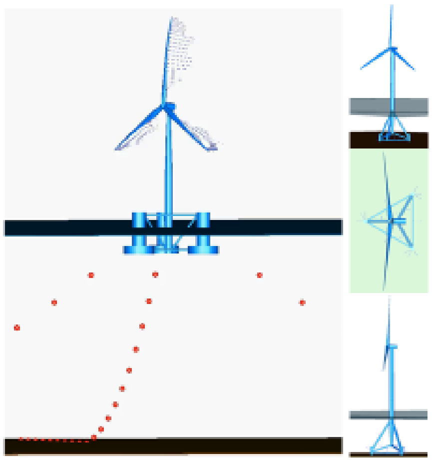
The quick way – Verification

Verification against other tools
- IWES code vs. GH Bladed vs. NREL FAST
- >100 Simulation cases
  - Basic structural properties (EF, mass,..)
  - Aerodynamics with rigid structure
  - Aero-elastic behavior
  - Operating Control
  - Stochastic wind and fatigue results
  - Offshore support structures and hydrodynamics

Verification with IEA OCx data
- OC3 Monopile, Tripod and Spar Buoy
- CO4 Floating Semisubmersible

Advantage
- Much "easier" than validation
  - No real data needed
  - Everything can be done in-house
- BUT results only as reliable as the software tools



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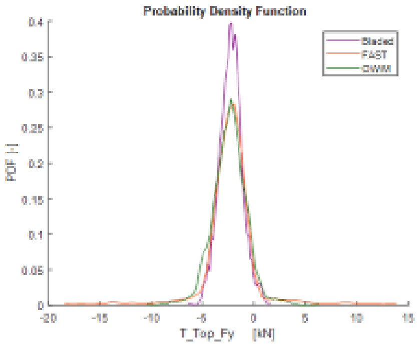
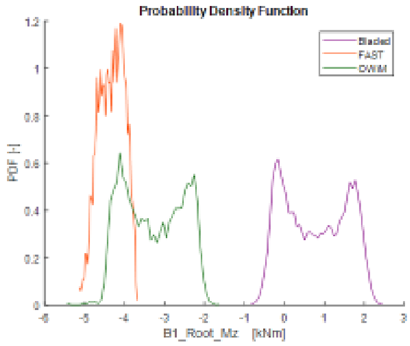
The quick way – Verification

Exemplary results
- Flexible turbine, power production
- Turbulent wind field at 9 m/s





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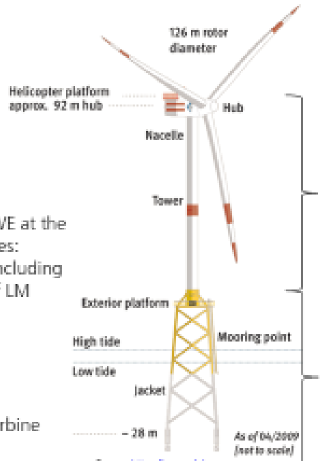
Verification and Validation in the IEA OC5 project

OC5 Phase III
- Senvion (Germany): Turbine data
- OWEC Tower (Norway): Jacket data
- Alpha Ventus wind farm: full-scale measurement data
- 38 participants from all over the world

Verification
- Against detailed turbine model available at SWE at the University of Stuttgart. The SWE model includes:
  - Detailed description of the entire OWT including structural and aerodynamic properties of LM Wind Power blades
  - Fully functional controller from Senvion
- Comparison of
  - mass and static forces
  - Natural frequencies and mode shapes
  - Power production of rigid and flexible turbine



Source:

Validation against measurement data until mid 2018

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Verification and Validation in the IEA OC5 project

First exemplary results

- Flexible turbine, power production
  check of tuned controller parameters with deterministic stepped wind changing from
  Vcut-in = 3 m/s to Vcut-out= 30 m/s,
  with a constant step of 1 m/s lasting for 50 s
- Generator torque plots

Below rated

Above rated

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Verification and Validation in the SmartBlades 2 project

Design
- Design of a 20 m bend-twist coupled rotor blade
- IWT-7.5-164 generic wind turbine
  https://www.windenergie.iwes.fraunhofer.de/en/press---media/iwes-wind-turbine- iwt-7-5-164.html

Implementation
- Construction of 20 m rotor blade at DLR in Stade, Germany
- Installation on a test wind turbine

Measurement
- Installation of measurement equipment
- Measurement of wind velocity and structural loads

Validation
- Code-to-Code Verification
- Validation

SmartBlades

SmartBlades 2.0

August 2019

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Verification and Validation in the SmartBlades 2 project

Data
- Blade design documentation
- Turbine model, including the controller
- Natural frequency of each blade after production
- Measurement data from test turbine
  - Wind velocities
  - Structural loads and deformations
  - Aerodynamic measurements
  - SCADA-Data

High-Fidelity Models
- CFD simulation of rotor aerodynamics
- FEM analysis of structural dynamics

Engineering Models
- Code-to-code Verification
- Validation of IWES aero-servo-elastic in-house code with measurement data

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Source: www.wind-turbine-models.com

Adwen AD 8-180 – research wind turbine

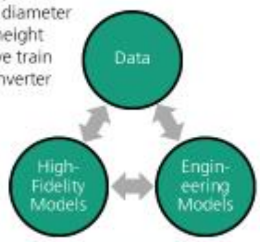
Research Turbine
- Owned by IWES, operated by Adwen

Data
- Detailed modelling data available
- Accredited measurements of mechanical loads and power performance according to IEC 61400-13 /-12
- Measurement of wind fields around the turbine

High-Fidelity Models
- Validation of wind physics modeling
- Validation of rotor aerodynamics modeling
- Validation of structure modeling

Engineering Models
- Validation of aero-servo-elastic tools

Key Figures
- 8 MW rated power
- 180 m rotor diameter
- 115 m hub height
- Modular drive train
- Full-scale converter



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Source: www.wind-turbine-models.com

Summary

- Code-to-code verification of engineering models easy to execute, but limited significance
- Engineering models
  - Rely on high-fidelity models
  - Aim to reproduce the behavior of high-fidelity models, but with less computational effort
- In the end: Everything depends on data
  - Reliability
  - Accuracy
  - Capability for cost reduction, increased reliability

→ Usually restricted access, esp. turbine and measurement

- Research turbines necessary!

Acknowledgements
Fraunhofer IWES is funded by the:

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Federal Ministry of Education and Research

European Regional Development Fund (ERDF):

Federal State of Bremen

- Senator of Civil Engineering, Environment and Transportation
- Senator of Economy, Labor and Ports
- Senator of Science, Health and Consumer Protection
- Bremerhavener Gesellschaft für Investitions-Förderung und Stadtentwicklung GmbH

Federal State of Lower Saxony

Free and Hanseatic City of Hamburg

Federal Ministry for Economic Affairs and Energy
Federal Ministry of Education and Research
European Union Investing in Bremen's Future European Regional Development Fund
Bremen
Lower Saxony
Hamburg

Thank You For Your Attention

Any questions?

philipp.thomas@iwes.fraunhofer.de

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DTU

Implementation Aspects of the Blade Element Momentum BEM Model for Aeroelastic Simulations of Large Wind Turbines

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Georg Pirrung
David Robert Verelst

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Department of Wind Energy

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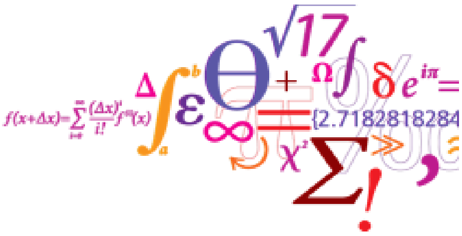

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Department of Wind Energy

Limitations of the BEM model for aeroelastic simulations

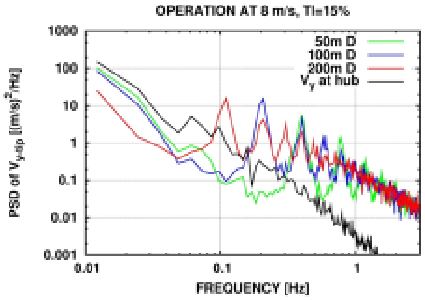
DTU

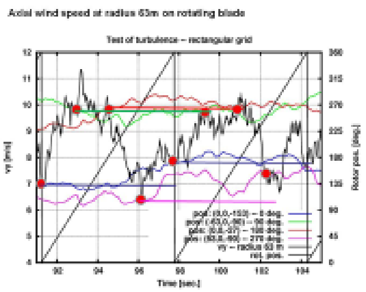
- ❑One dimensional
- ❑Steady
- ❑Axis-symmetric

This is far from the conditions on a real turbine which are unsteady and non-axis symmetric due to inflow with **shear** and **turbulence** and due to operation with a **yaw** and **tilt** angle of the turbine.

Turbulent inflow – non axisymmetric inflow

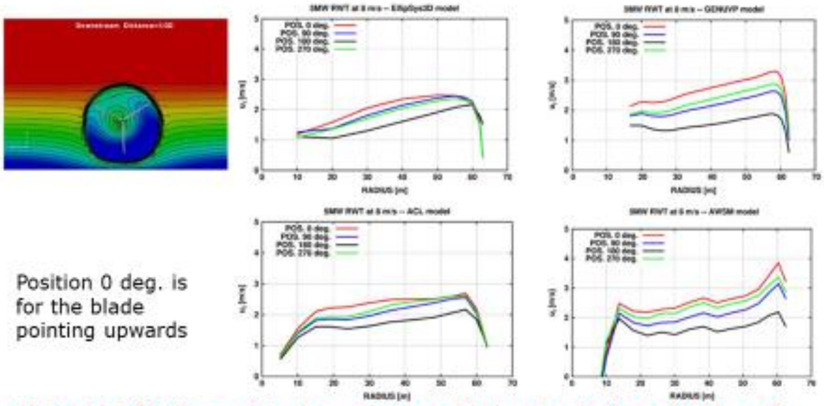
DTU





1p, 2p 3p ….. content in the inflow seen from the blade increases with turbine size

What can we learn from high fidelity models ? – results from the Upwind EU project 2010



Position 0 deg. is for the blade pointing upwards

All the high fidelity models show variation of induced velocity as function of azimuth for sheared inflow – here a case with 0.5 in shear exponent – **not axis-symmetric induction**

Aagaard Madsen, H., Riziotis, V., Zahle, F., Hansen, M. O. L., Snel, H., Grasso, F., ... Rasmussen, F. (2012). Blade element momentum modeling of inflow with shear in comparison with advanced model results. Wind Energy, 15(1), 63–81. doi:10.1002/we.493

The BEM model – momentum equation for a ring element – stream tube

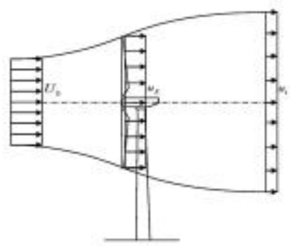


Fig. 3.1 Control volume for one-dimensional actuator disc.

$$T = 2\rho A U_0^2 a(1-a) \quad where \quad a = \frac{U_0 - u_r}{U_0}$$

Nørkær Sørensen, Jens. General Momentum Theory for Horizontal Axis Wind Turbines. Springer, 2016.

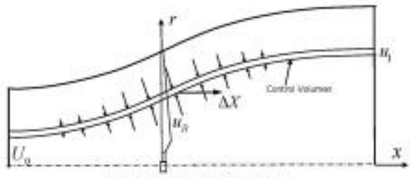


Fig. 3.4 Control volume of differential annulus.

$$\Delta T = 2\rho \Delta A U_0^2 a(1-a) \quad where \quad \Delta A = 2\pi r \Delta r$$

H. Glauert 1935

Thus, by considering the flow in a tunnel and then proceeding to the limiting condition of a tunnel of very large radius, it has been possible to establish the validity of the momentum equation applied to the propeller as a whole. This simple line of argument does not suffice to establish the form of the momentum equation applied to the separate annular elements of the propeller, but in the development of the theory it is customary to replace the integral (2.9) by its differential form

$$\left.\begin{aligned} dT &= \rho u_1 (u_1 - V)\, dS_1 \\ &= \rho u (u_1 - V)\, dS \end{aligned}\right| \qquad (2.10)$$

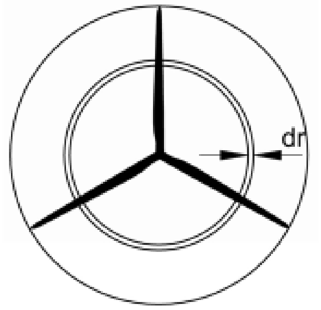
The validity of this equation has not been established[1] and its adoption may imply the neglect of the mutual interference between the various annular elements, but the actual deviations from the conditions represented by (2.10) are believed to be extremely small in general.

Aagaard Madsen, H., Bak, C., Døssing, M., Mikkelsen, R. F., & Øye, S. (2010). Validation and modification of the Blade Element Momentum theory based on comparisons with actuator disc simulations. Wind Energy, 13(4), 373–389. doi:10.1002/we.359

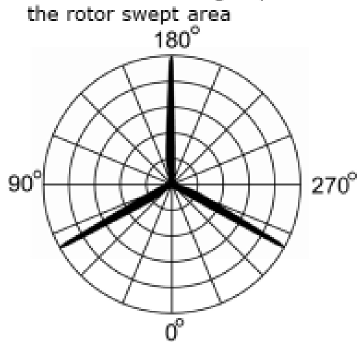
Two different implementations of the BEM model

DTU

Mean induction in a ring element



Local induction on grid points over the rotor swept area



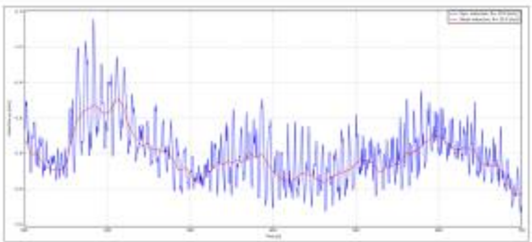
$\Delta T = 2\rho\,\Delta A\,U_0^2\,a(1-a)$ *where* $\Delta A = 2\pi\,r\,\Delta r$

$\Delta T = 2\rho\,\Delta A\,U_0^2\,a(1-a)$ *where* $\Delta A = 2\pi\,r\,\Delta r\,\Delta\varphi$

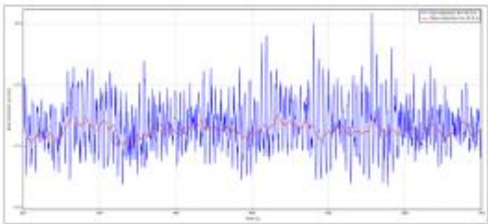
Turbulent inflow – dynamic and mean induction

DTU

AVATAR 8 m/s



AVATAR 18 m/s

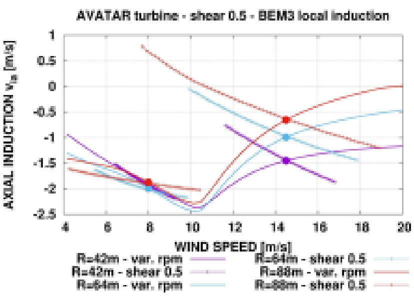


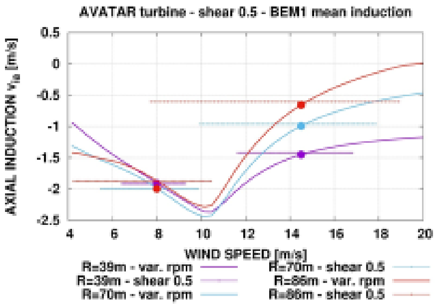
Two different implementations of the BEM model

- What impact has the two different implementations on loads and fatigue for inflow with shear and turbulence ?
- What is the mechanism between the difference in loading ?

Mechanism of induction in sheared inflow from the two implementations

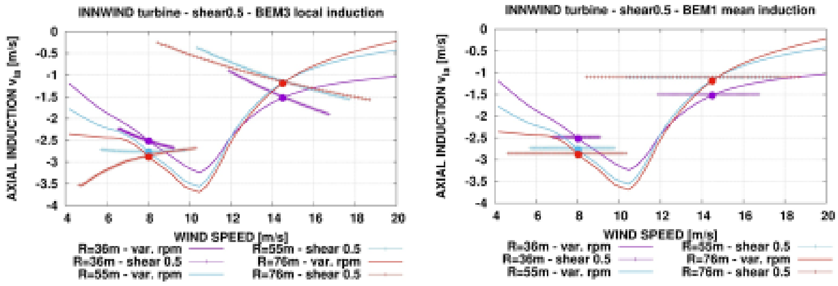
The AVATAR turbine is a so-called **low induction** rotor





Mechanism of induction in sheared inflow from the two implementations

The Innwind is a copy of the 10MW DTU RWT – normal rotor design



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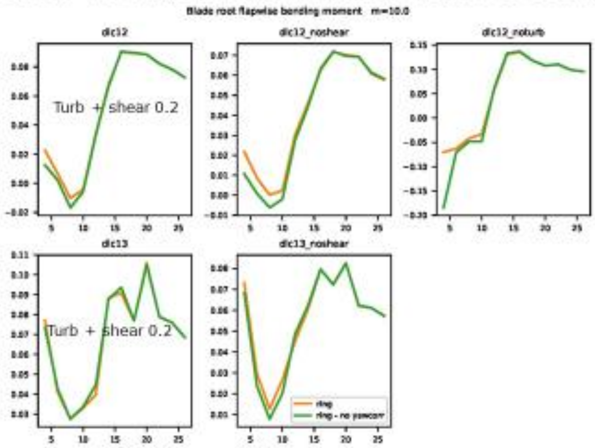
Presentation at IEA Wind task 11 - Topical Expert Meeting #88 - 6th-8th of September in Scotland

Aeroelatic simulations for the Innwind RWT

– DEL loads for ring BEM implementation relativ to local (grid) BEM



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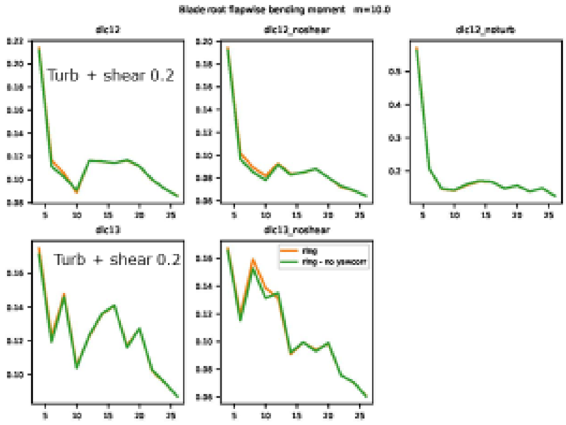

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Conclusions

- ❑ It has been demonstrated that different implementations of BEM can have an important impact on computed aero fatigue loads for operation in shear and turbulent inflow
- ❑ An implementation of BEM, modelling local induction will in general give lower fatt. loads in the range from 0-20% when compared with a BEM implementation computing the mean induction in a ring element
- ❑ The impact is strongest on low induction rotors

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Thank you

CL-Windcon

Closed Loop Wind Farm Control

IEA WIND TASK 11 – TOPICAL EXPERT MEETING #88
6th – 8th September, 2017
Scotland

Javier Sanz
CENER

CL-Windcon

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727477

CL-Windcon

CLOSED LOOP WIND FARM CONTROL

- H2020 European funded project
- Coordinator: National Renewable Energy Centre of Spain (CENER)
- 14 partners from 6 European countries
- Duration: November 2016 – October 2019 (36 months)
- Total cost: 4.931.422,50 EUR

Aerodynamic wind farm control: CL-Windcon will address **multi-fidelity dynamic modelling** and **open and closed-loop advanced control algorithms at a farm level** by treating the entire wind farm as a comprehensive real-time optimization problem.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727477

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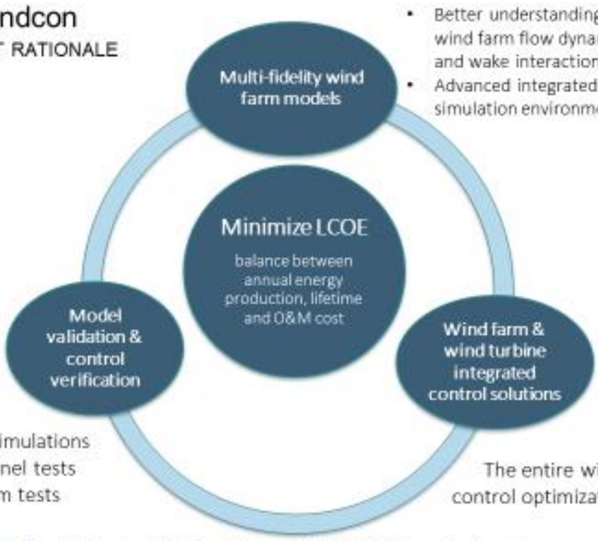
PROJECT RATIONALE

- Better understanding of wind farm flow dynamics and wake interactions
- Advanced integrated simulation environments



- SOWFA simulations
- Wind tunnel tests
- Wind farm tests

The entire wind plant as a control optimization problem

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727477

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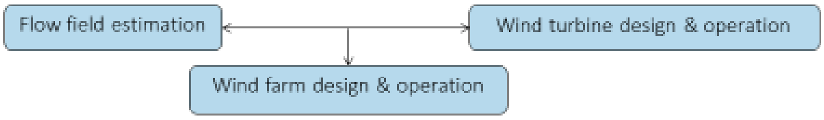
CHALLENGES



- Integration of different temporal and spatial scales and model fidelities
- Validation of CFD models against:
  - Wind tunnel tests
  - Wind field data
- Comparison among different multi-fidelity models: from CFD to control-oriented engineering models
- Multiple criteria optimization: production maximization & minimal loading by acting on aerodynamic interaction
- Unusual points of operation for wind turbines (e.g. yaw redirection)
- Control verification of different strategies: yaw redirection, derating

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727477

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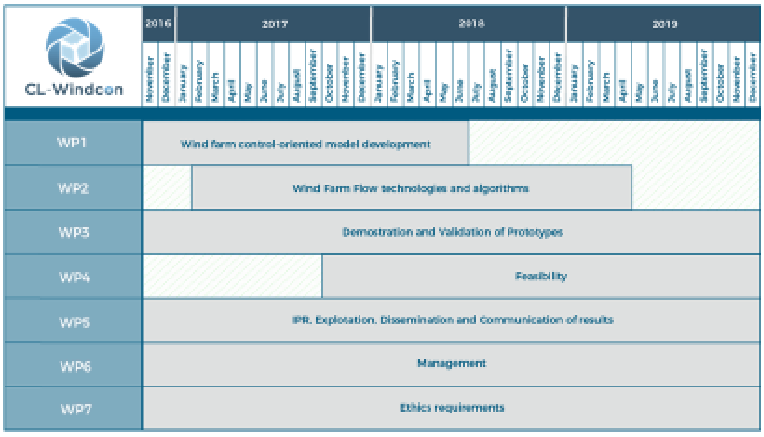
PLANNING



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CURRENT STATUS

- Tasks already performed:
  - Definition of reference wind farms, simulation scenarios and use cases
  - Definition of the preliminary test matrix for wind tunnel experiments (wake characterization and tool validation)

- On-going work:
  - Evolution of a set of multi-fidelity wind farm modeling tools, setting an adequate comparison framework
  - Creation of SOWFA reference simulation environment
  - Optimal wind turbine control strategies aimed at wind farm control
  - Wind farm control strategies (axial induction, wake redirection)
  - Detailed planning of full scale testing

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THANK YOU!

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www.clwindcon.eu

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Aeroelastic Simulation of Wind Turbines

Tool Development and Validation

Oliver Hach, DLR-AE

DLR

DLR Institute of Aeroelasticity

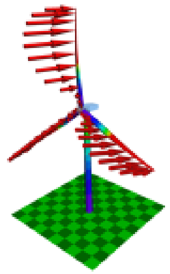
Wind power activities

- in the previous past (GROWIAN)
- joint DLR initiative since ~5 years
- currently major focus on development of methods and tools

DLR Institute of Aeroelasticity

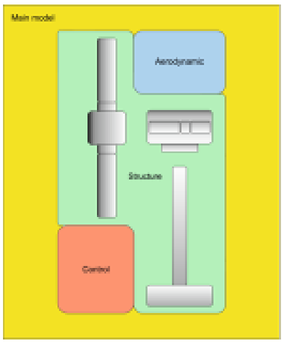
DLR

Aeroelastic Modelling



Automatic Model Generation „TurbGen“

- generates MBS (Simpack) models including
  - elastic bodies (Ansys/FlexModal)
  - wind (currently limited to Aerodyn v13)
  - external controller libraries
- additional interfaces
  - FMUs possible for use of external models (generator, drive train, actuators)
- drag-and-drop exchangeability of subcomponents



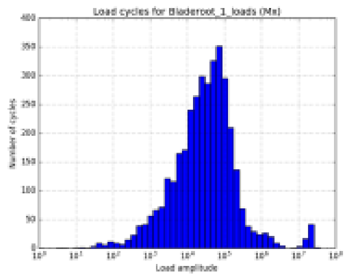
DLR

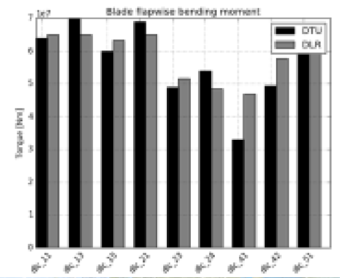
Aeroelastic Loads

Automatic load calculation “TurbLoads“

- IEC 61400 load cases (start/stop/production/a few error cases)
- inputs: generated MBS model, TurbSim und IECWind
- parametric definition of load cases (= DLC)
- automatic execution and processing of results (ultimate and fatigue loads, kinematics)
- post-processing: inertial loads (used for structural optimization)

DTU 10 MW RWT

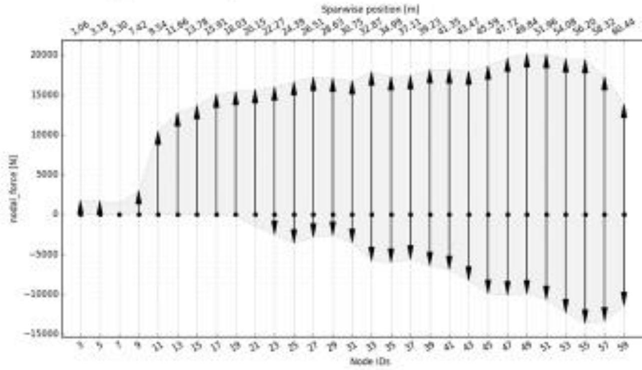




DLR

Aeroelastic Loads

NREL 5MW RWT (x), nodal aerodynamic loads

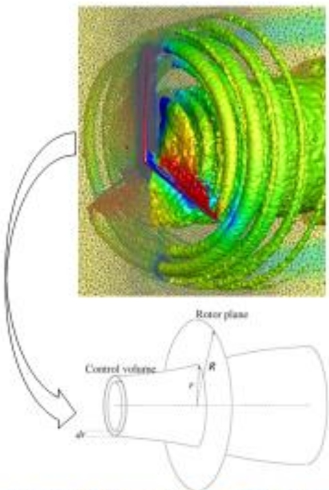


DLR

Fast engineering models enhanced by CFD data

- **Transfer** from high-fidelity CFD simulations to fast engineering models

- **Steady-state modelling**: Extraction of airfoil data from 3D RANS simulations of a rotor
- **Unsteady modelling**: CFD-based higher order models, describing the dynamic wake effect
- **Nonlinear modelling**: Nonlinear behavior due to large perturbation in the operating conditions or due to large control surface deflections; description by reduced-order models



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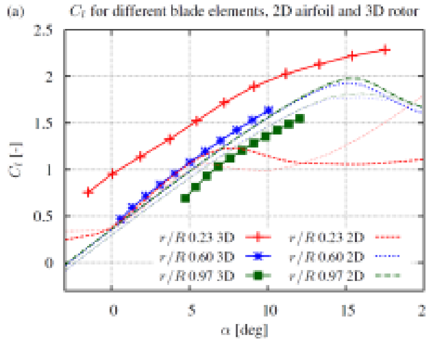
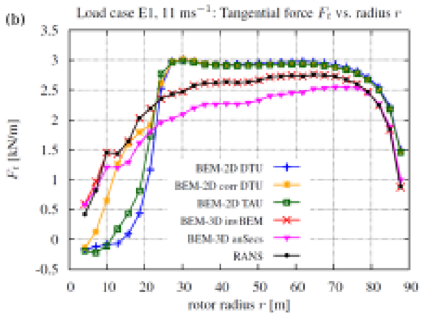
Fast engineering models enhanced by CFD data - steady-state



Lift coefficients extracted from steady-state 3D rotor RANS simulations (lines with symbols) vs. common 2D airfoil coefficients (lines only)

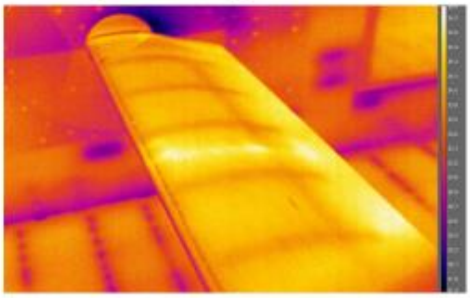


Radial load distribution (tangential force) from RANS (black), enhanced BEM (red) and common BEM results (other colors)

Fast engineering models enhanced by CFD data

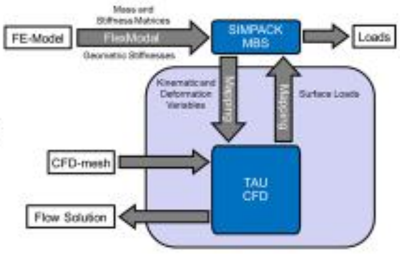
- **Verification**: Comparison to CFD training data
- **Code-to-code validation**: Comparison to CFD data for another case, which was not used for model identification
- No satisfactory data (at DLR) for validation against **rotor experiments**

S809 airfoil in Transonic Wind Tunnel Göttingen



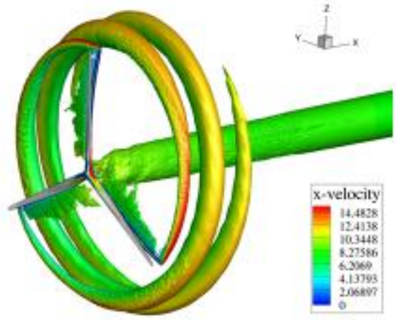
Infrared picture showing transition line close to the nose

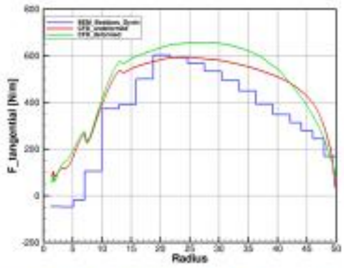
High Fidelity Aeroelastics



Steady-state/unsteady CFD-MBS coupling

- weak coupling of DLR-Tau and Simpack solver



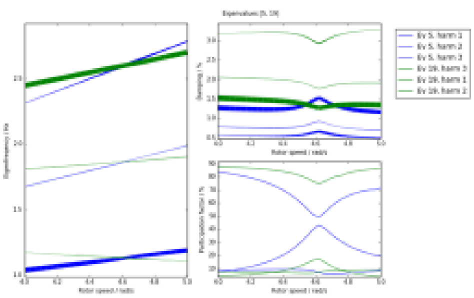


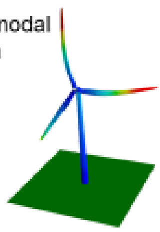
DLR

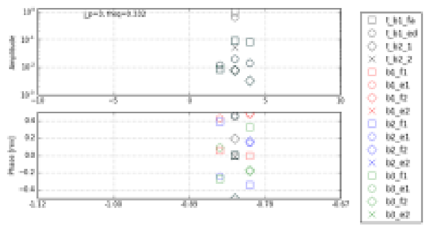
Aeroelastic Stability

Stability analysis toolbox „STARS" for rotating systems

- time domain data of analytical models, Simpack models
- basis: Floquet Analysis, Partial Floquet Analysis
- result: periodic „mode shapes", multiple eigenvalues, participation factors, modal harmonic composition







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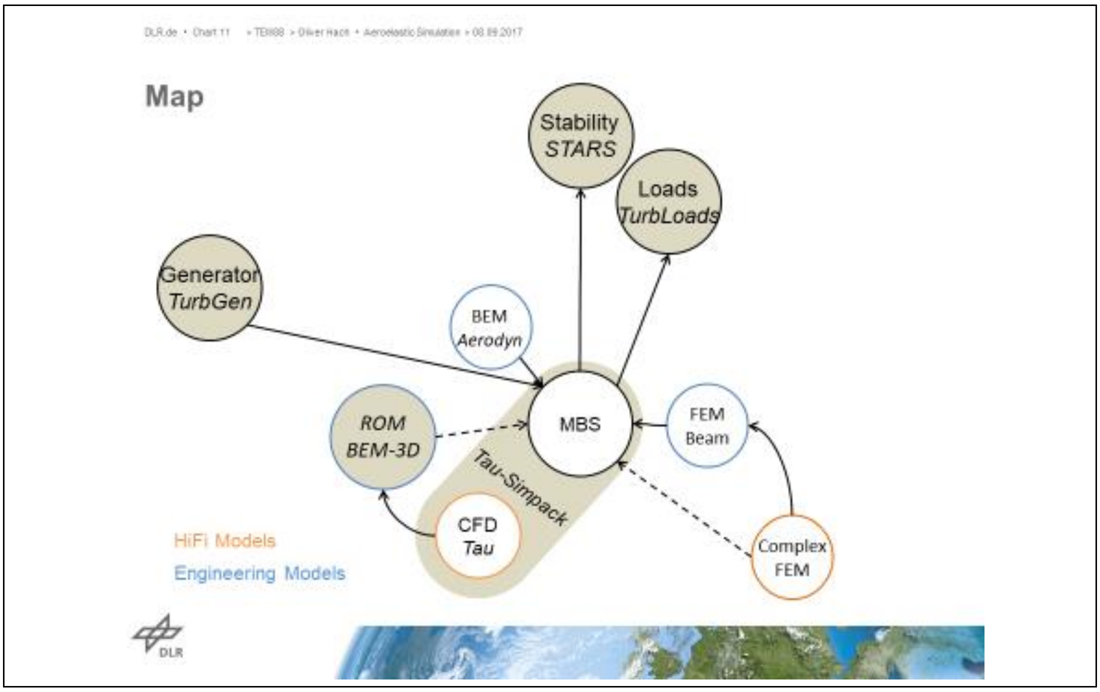
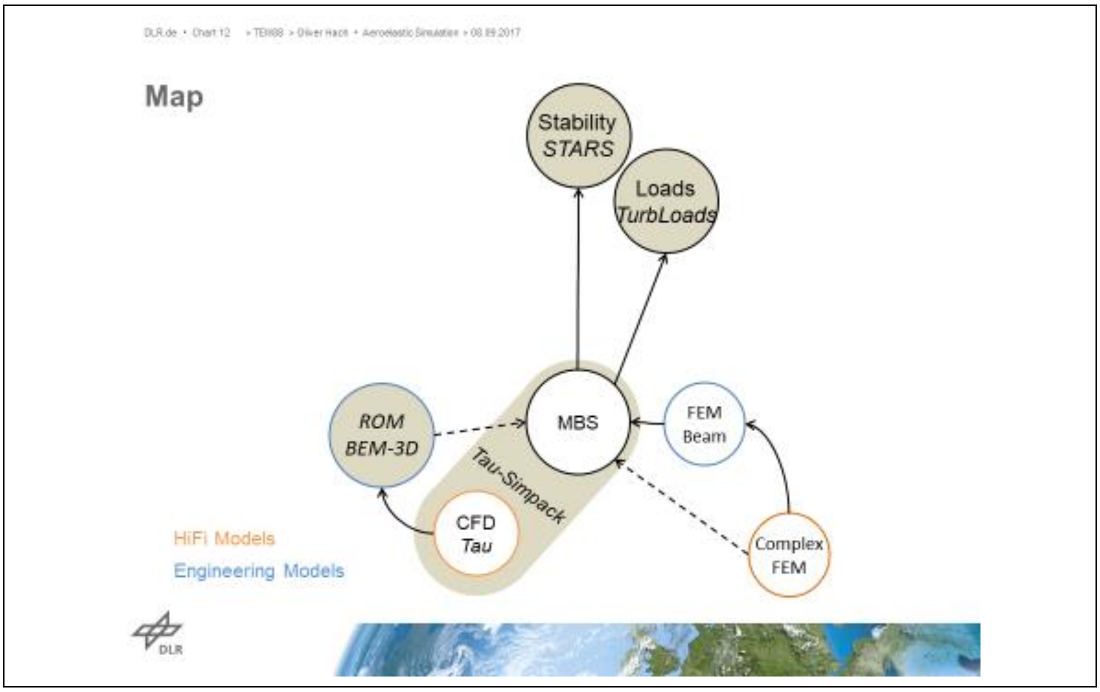

DLR.de • Chart 11
Oliver Hach
Aeroelastic Simulation
08.09.2017
Map
Stability
STARS
Loads
TurbLoads
Generator
TurbGen
BEM
Aerodyn
ROM
BEM-3D
MBS
FEM
Beam
Tau-Simpack
CFD
Tau
Complex
FEM
HiFi Models
Engineering Models
DLR


DLR.de • Chart 12
Oliver Hach
Aeroelastic Simulation
08.09.2017
Map
Stability
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TurbLoads
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MBS
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Beam
Tau-Simpack
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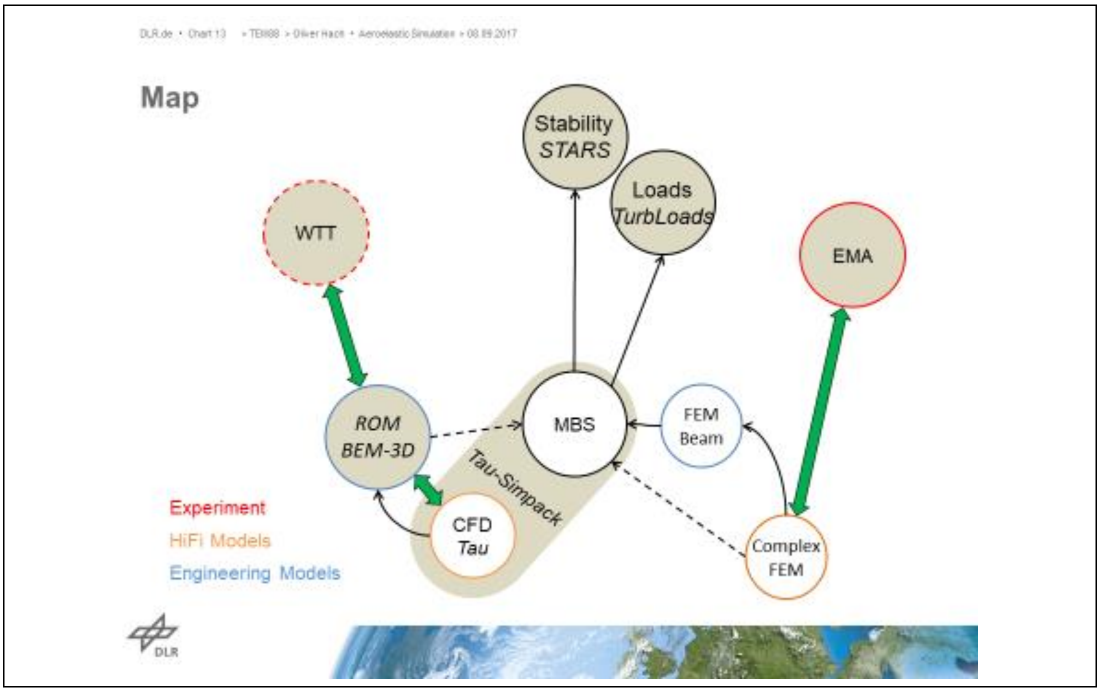
FEM
HiFi Models
Engineering Models
DLR


DLR.de • Chart 13 • TEI688 > Oliver Hach • Aeroelastic Simulation • 08.09.2017
Map
Stability
STARS
Loads
TurbLoads
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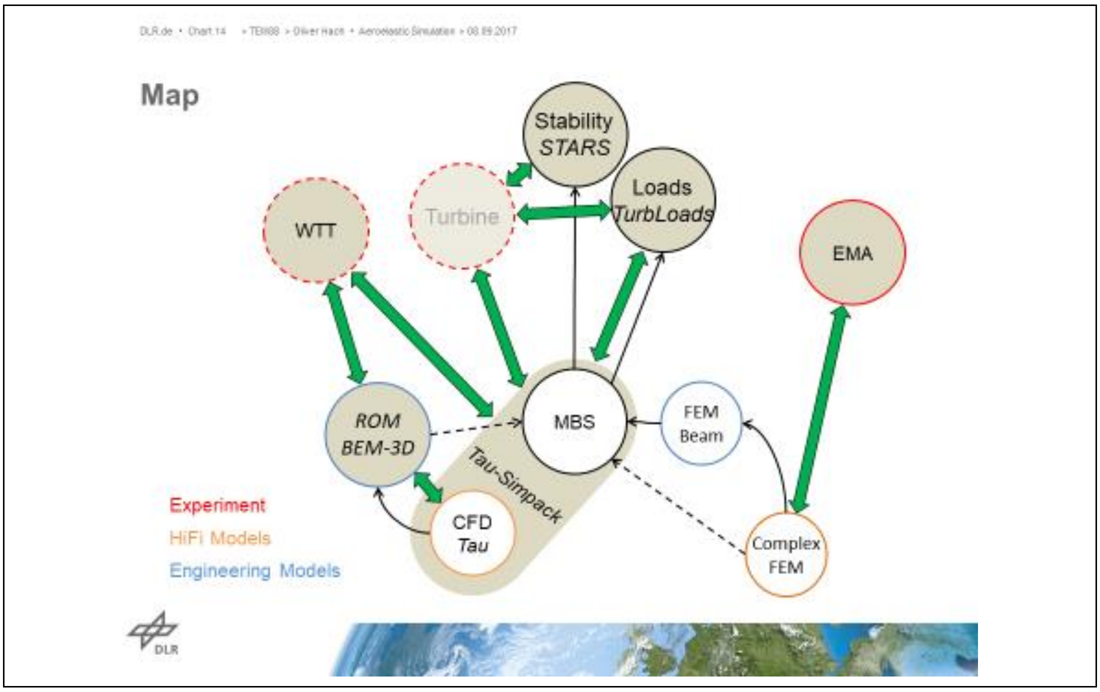
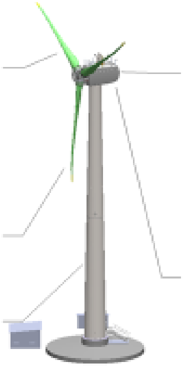
Complex
FEM
Experiment
HiFi Models
Engineering Models
DLR


DLR.de • Chart 14 • TEI688 > Oliver Hach • Aeroelastic Simulation • 08.09.2017
Map
Stability
STARS
Turbine
Loads
TurbLoads
WTT
EMA
ROM
BEM-3D
MBS
FEM
Beam
Tau-Simpack
CFD
Tau
Complex
FEM
Experiment
HiFi Models
Engineering Models
DLR

Full scale wind turbine: ExpTurb

- **Design** phase ended in 05/2017
- Based on commercial WT (750 kW)
- Designed for experimental operation: upwind/downwind, control system, loads

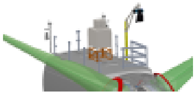


Rotor
Blade as specified by DLR
- similarity to Multi-MW turbines: slender blades, 105 m/s blade tip speed
- modular tip section at 1,2 m

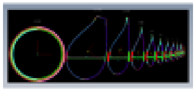
Blade access
- lift

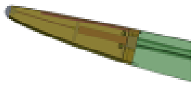
Tower
- max deflection < 6 cm

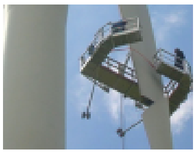
Drive train
- torque measurement
- gear ratio
- bi-directional



Nacelle
- rooftop crane
- LiDAR mounting platform







Acknowledgements to the team:
Alexander Klawonn, Felix Wienke, Marc Schneider, Simon Hammen

Thank you for the attention!

CHARACTERIZATION OF AND CHECKS ON SENSOR DATA FOR MODEL VALIDATION

Jean-Baptiste Le Dreff, EDF R&D, ERMES Dpt
James McNaughton, EDF Energy, UK R&D Centre
Elisabeth Duranteau, EDF R&D, ERMES Dpt

IEA Wind Task 11 – Topical Experts Meeting Sept 2017

DATA & OBJECTIVES

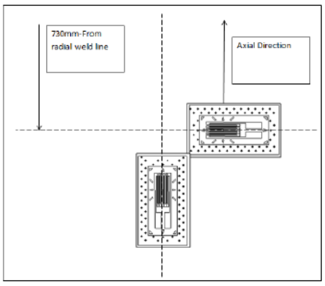
- **Global aim: Validate computational model with in-field data**
- **Data available:**
  - Wind turbine instrumented
    - Different locations on the transition piece (monopile foundations)
    - 1 year of data during operation (2016)
  - Environmental parameters: wind & waves

1st Step

- **Check the reality of the measurements:**
  - Is data realistic ? Can we check that we are getting coherent results ? Are they meaningful from a physical point of view ? Is it necessary to delete some parts ? What can be learned from the relationship between wind/meteocean and measurements ?
- **-> Characterize measurement data (in progress)**
  - Correlate strain measurements with wind and waves
  - Extend to DEL
  - Correlate measurements between different strain gauges
  - Study influence of weld on stress concentration

CONTEXT - LOCATION OF STRAIN GAUGES

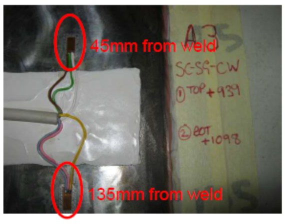
- **Characteristics:**
  - T-gauge configurations and single axial gauges
  - On transition piece at locations around the circumference



Type of Gauge	Location	Angle around circumference (0deg = North) [deg]
T-Gauge configuration	730 mm below radial weld line	30 ; 60 ; 210 ; 240
Single Axial Gauges	730 mm below radial weld line	135 : 315

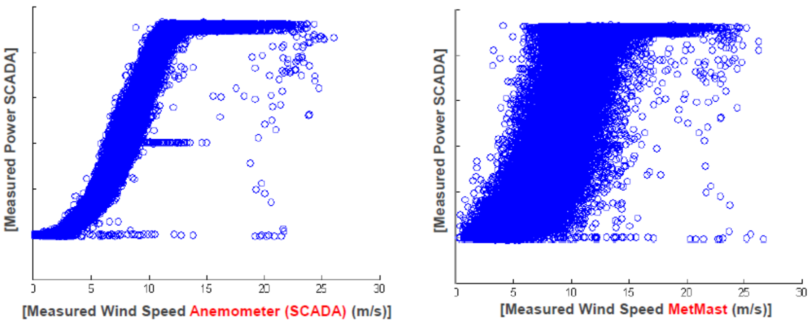
CONTEXT - LOCATION OF STRAIN GAUGES FOR STRESS CONCENTRATION

- **Strain gauges installed to look at stress concentration around welds**
  - Close to circumferential weld
  - At 0.5 and 1.5 times the thickness of the TP material



Type of Gauge	Location	Angle around circumference (0deg = North) [deg]
Circumferential weld gauge	45 mm and 135 mm below circumferential weld line	45 ; 225

CONTEXT - WIND MEASUREMENTS CORRELATION



- Problem of correlation of met mast wind data -> use of anemometer

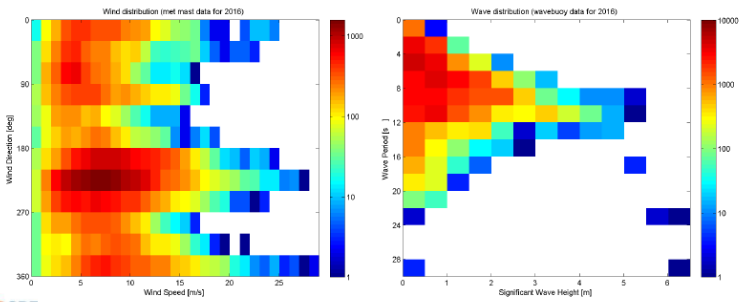
CONTEXT - LOAD CASES

- Load case repartition in order to classify results by intervals of 10min

  More than 50000 intervals, 7319 load cases

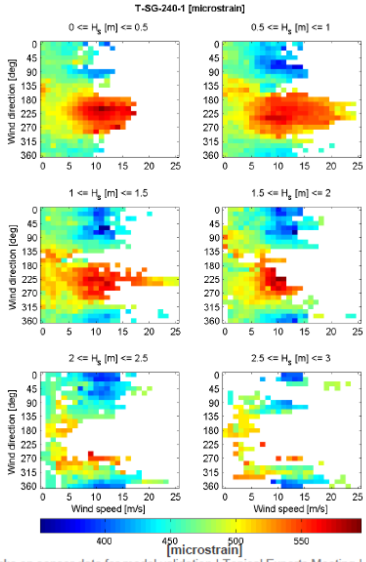
  -> Study global results over the year by averaging over each interval

Variable	Bin size
Wind speed	1 ms^{-1}
Wind direction	30°
Significant wave height	0.5 m
Peak wave period	2 s
Peak wave direction	30°



ANALYSIS - CORRELATION FOR GIVEN DIRECTION

- **Axial strain gauge aligned with 240 deg**
  - highest strain values for winds around 240 deg in all sea states -> good correlation
  - Bad calibration of data: not oscillating around 0 -> will be a problem for model validation -> look at time history to see if drift can be observed and quantified



ANALYSIS - CORRELATION FOR GIVEN DIRECTION

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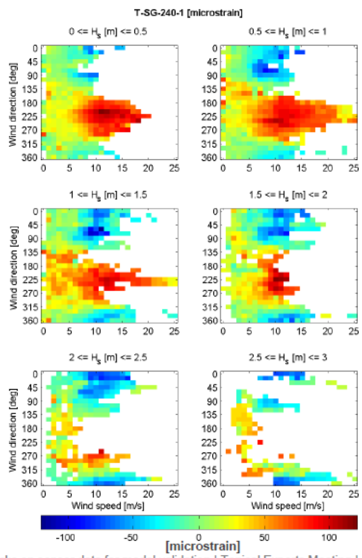
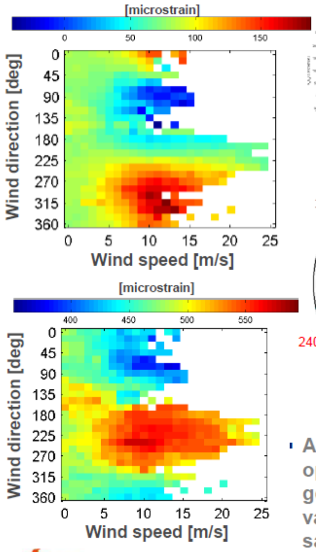
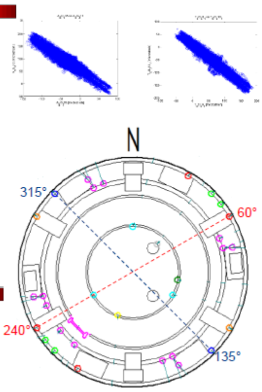
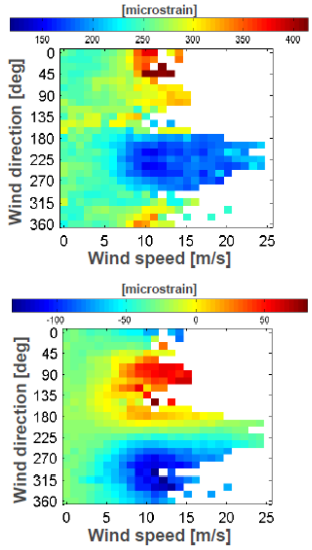


ANALYSIS - CORRELATION FOR OPPOSITE GAUGES

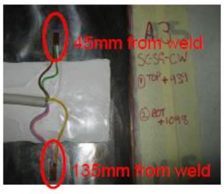


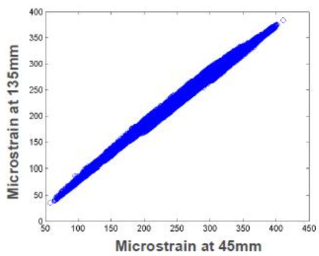




- Axial strain gauges in opposite locations -> very good correlation in variations but not values : same issue of calibration

ANALYSIS - INFLUENCE OF WELD

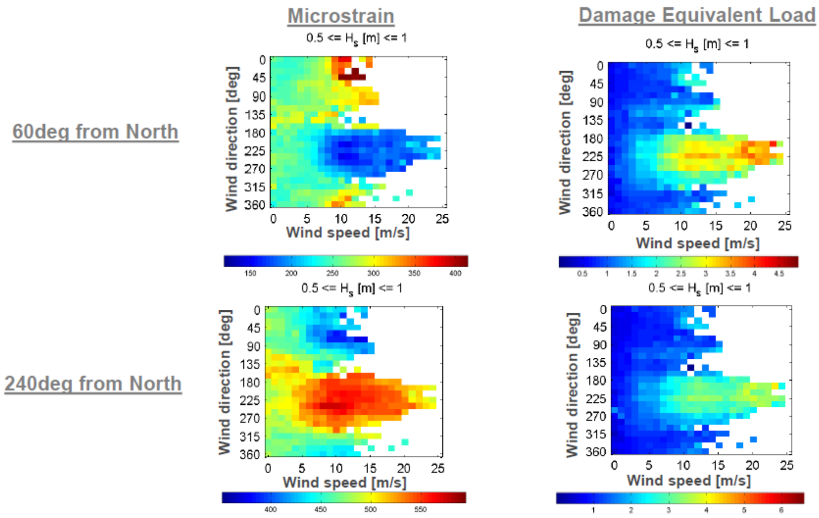




! Calibration might be wrong !

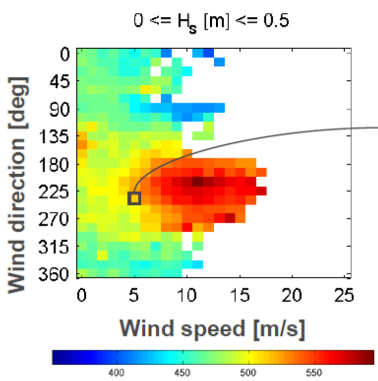
- Small dispersion -> good precision & no drifting of the material properties with time
- Effect of weld is linear with the strain
- Influence of weld to be determined after calibration has been analysed because it depends on:
  - Slope of curve
  - Whether it goes through (0 ; 0)

ANALYSIS - INFLUENCE ON DAMAGE

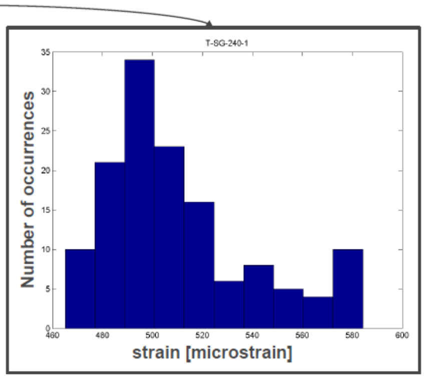


- Less damage for wind from 60° → seems to indicate a wake effect

ANALYSIS – LOAD CASE INTERNAL VARIABILITY



- Focusing on all 10-min results tagged into one same load case
  - Wind speed=5m/s
  - Wind direction=240°
  - Hs=0,5m



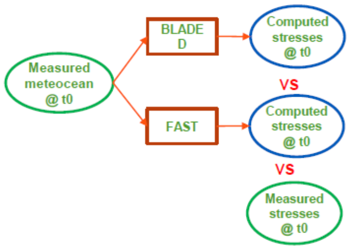
➢ Strong variability in one well defined load case; need further investigating

CONCLUSIONS & FUTURE WORK

- **Sensors – completed:**
  - Good correlation between sensors for different directions and locations -> ok from physical point of view
  - Effect of weld looks linear with strain value
  - Potential effect of wake on damage
  - Internal variability is significant

- **Sensors**
  - Solve calibration issues (look at potential temporal shift)
  - Investigate internal variability
  - Study influence of weld on stress concentration
  - Focus on time history
  - …

- **Models + Sensors**



→ *Can we model a specific load case?*

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Wind Farm Aerodynamics Group – IEA Task 11 TEM #88

Patrick Moriarty

September 8, 2017

Fundamental Question

Should IEA Wind establish one or more collaborative(s) involving three-way V&V between data, HFM, and engineering models....?

Fundamental Answer

YES!

....and what could that look like?

- Continuation of Task 31: Wakebench

- Observations
  - Time resolved (mesoscale) higher resolution quantitative comparisons between models and observations
  - Comparison to planar/volumetric data sets
  - Continued collaboration with industry essential
  - Improved SCADA data analysis (underperformance identification)
  - Long-term (extremes and converge statistics) and short-term (high fidelity observations of specific phenomena)
  - Loads (new), simultaneous inflow (ABL) and wakes
  - Many new data sets coming in 2018 – A2e and NEWA
  - Interest in subscale? Fundamental building blocks – validation hierarchy justification

- Models
  - All fidelities, including statistical/surrogate models
  - Coupled with mesoscale
  - Quantify improvement in industry tools – more physics in engineering models

....and what could that look like? (cont.)

- Long Term Goals
  - 10% standard deviation of wake loss with no bias
    - E.g. wake loss = 20% -> std. dev. 2% in AEP estimate
  - Accurate forecast to predict overall wind farm output to alleviate intermittency concerns
  - Bias free turbine pad power production/AEP estimates
  - Loads metric (new experiments)
    - Fatigue within 10%
    - Extreme -match mean of max within wind speed and sector within 20% for 10 load case
  - Requires standard baseline wind farms
- Near Term Activities
  - Consensus on important phenomena i.e. international PIRT
    - Web-based questionnaire and annual meetings for updates
    - Overlap with current funding opportunities
  - Internationally designed experiments
    - Summary of existing datasets
    - Important phenomena
    - Required instrumentation – development needs
  - International white paper to attract multilateral funding and data opportunities
  - Improved benchmarking process

....and what could that look like? (cont.)

- Improved benchmarking
  1. Detailed description of benchmark set up and inputs
  2. Blind comparison
  3. Calibration
  4. Iteration
  - Hierarchy approach, start simple move toward complex
  - Multiple metrics for each benchmark

- Physics
  - Two-way coupling issues e.g. blockage, channeling
  - Mesoscale-microscale e.g. wind direction uncertainty, land/sea, terrain
  - Driving wake physics e.g. turbulent length scales
  - Off design conditions to demonstrate value of higher fidelity e.g. LLJ

- Modeling and observations combined
  - Use HFM to design experiments
  - Use HFM to interrogate and analyze observations
  - Sensitivity analysis using models to determine most important phenomena
  - Engineering models fill in statistics
  - Multi-fidelity UQ

NATIONAL RENEWABLE ENERGY LABORATORY 6

....and what could that look like? (cont.)

- Uncertainty Quantification
  - Feedback fundamental uncertainties to P99/P50 or other industry relevant metric
  - Work on common vocabulary for UQ
- Collaborations
  - Joint experimental planning with IEA Task 29
  - IEC -15, PCWG, and AWEA Wind plant power group
    - Propagation of improved uncertainty estimates to industry relevant metrics
  - Data sharing with IEA Task 30 e.g. Alpha Ventus
  - Remote sensing experience from IEA Task 32
  - Mesoscale overlap with IEA Task 36
  - Joint workshops
- Potential Roadblocks
  - Scattered focus
  - Funding
  - Confidentiality

NATIONAL RENEWABLE ENERGY LABORATORY 7

A2e Wind Farm PIRT

Phenomenon	Importance at Application Level	Model Adequacy Physics	Model Adequacy Code	Model Adequacy Val
Inflow Turbulence/Wake Interaction				
Wind direction (shear/veer/asymetry)	H	L	M	M
Turbulence characteristics (intensity, spectra, coherence, stability)	H	L	M	M
Coherent turblence structure	H	L	M	L
Surface conditions (roughness, canopy, waves, surface heat flux, topography)	H	L	M	M
Momentum transport (horizontal and vertical fluxes)	H	L	L	L
Multi-Turbine Wake Effects				
Wake interaction, merging, meander	H	L	L	L
Plant flow control for optimum performance	H	M	M	L
Wake steering (yaw & tilt effects)	H	L	L	L
Wake dissipation	H	L	L	L
Wake Impingement (full, half, etc.)	H	L	L	L
Deep array effects (change in turbulence, etc.)	H	L	L	L
Other Effects				
Wind plant blockage effects and plant wake	M	M	M	L
Acoustic Propagation	H	L	L	L

Questions?

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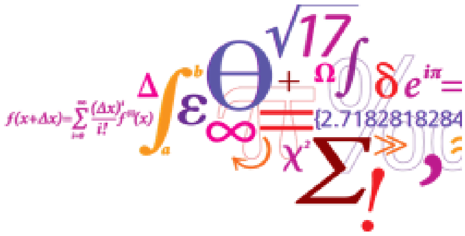
Break-Out Session

Rotor Aeroelastics

Helge Aagaard Madsen
Carlos Rodriguez

Section AER
Department of Wind Energy

hama@dtu.dk



DTU Wind Energy
Department of Wind Energy

Aeroelastic modelling - from breakout discussion day 1

A brainstorm about areas/subjects with considerable uncertainties

1. Inflow – turbulence and shear
   - Variation of turbulence intensity (TI) as function of height
   - High TI variations in flow over forest
   - Complex variation of TI as function of height during periods (morning/evening) where there is a shift from stable to unstable atmospheric flow
2. Impact of the TI and its variation
   - Loads not directly related to TI but also to stability effects
   - Loads should be simulated for specific site conditions
   - Present standard is not covering the complexity of TI
   - Sensitivity of turbulence parameters important to clarify
3. How to model variation of TI and other turbulence characteristics
   - Several turbulence boxes
   - LES simulated inflow

Aeroelastic modelling - from breakout discussion day 1- contd

A brainstorm about areas/subjects with considerable uncertainties

5. New blade designs – aeroelastic tailored – BTC
   - Uncertain how well we model sweep of blades
   - Use of more advanced models than BEM
5. Elastic torsion of blades –how to measure it
   - Methods investigated in the German SMART blade project
   - 20m blade with BTC will be manufacture.
6. How to model BTC blades - structurally
   - Coupling issues going from full FEM model to e.g. multibody simulation in an aeroelastic model
   - To overcome confidential issues on blade structural data – could it be transferred directly through stiffness and mass matrices
7. UQ models and theories
   - Tools to propagate uncertainty through simulation models

Aeroelastic modelling - from breakout discussion day 1- contd

A brainstorm about areas/subjects with considerable uncertainties

8. Subjects from the round at the end
   - Modelling of advanced blade designs like BTC and swept designs
   - Dynamic stall and deep stall
   - Standstill blade modelling
   - Swept blades – 3D flow effects
   - More advanced structural testing of blades
   - Storm conditions - in the new IEC standard
   - Simulation at high yaw errors
   - Uncertainty in simulation of derated turbines – stability issues
   - Simulation capability of future designs – large blades – flaps – multi rotors
   - Site specific loads
   - Collaboration to ensure progress

Questions to Guide the Discussion on Rotor Aeroelastics - 1

1. Where is the greatest uncertainty & conservatism in existing models limiting technology improvement?
   - Aroelastic modelling of new slender blades with BTC and e.g. sweep and out of plane bending
   - Modelling complex inflow and its influence on aeroelastic response
   - Multirotor designs
2. What level of model fidelitity (HFM <-> engineering models) is needed in each technology development step?
   - CFD models (HFM) often used to check airfoil and blade designs at an early stage and maybe give input (airfoil polars) to further engineering modelling
   - If it is a new concept it might be a lower fidelity model type that is used for the early investigations
3. How can HFM be used to develop/calibrate/validate engineering models?
   - System identification methods using CFD simulations as basis (wake flow, rotor flow)
   - Library of LES inflow flow fields

5 DTU Wind Energy, Technical University of Denmark — Rotor Aeroelastics - break out group IEA Wind task 11 - Topical Expert Meeting #88 - 6th-8th of September in Scotland

Questions to Guide the Discussion on Rotor Aeroelastics - 2

4. Can surrogate models be a good substitute for physics-based engineering models?
   - Maybe for certain experiments like tow tank testing.
5. What physical insights should be targeted by HFM & experimentation?
   - Characterization of complex inflow
   - Rotor induction interaction with turbulent inflow – one-way/two-way interaction (BEM<>bend-twist coupling)
6. What relevant experimental datasets are available & what data is still needed?
   - Mexnext data base
   - New Mexnext – DANAERO
   - Levenmouth-CLOWT database?
7. Is V&V of HFM done in conjunction with, or before, engineering model V&V?
   - Better in conjunction with

6 DTU Wind Energy, Technical University of Denmark — Rotor Aeroelastics - break out group IEA Wind task 11 - Topical Expert Meeting #88 - 6th-8th of September in Scotland

Questions to Guide the Discussion Rotor Aeroelastics - 3

8. Should V&V focus on steady-state (e.g. power) or time-resolved (e.g. loads) physics?
   - Time resolved loads will be the focus
9. What metric should be used to quantify validation success or failure?
   - Enough data to compare, use standard deviations and quantify errors
10. What is the role of UQ in the V&V effort?
    - xx
11. What are the long-term goals of the collaborative(s)?
    - xx

Questions to Guide the Discussion Rotor Aeroelastics - 4

12. What should be the initial focus of the collaborative(s)?
    - Xx
13. Who and with what software are interested in participating in the new collaborative(s)?
    - A good contribution of different fidelity codes is expected from DLR, IFE,DTU and other participants like ORE Catapult (Task 29)
14. Should the new collaborative(s) proceed as extensions of IEA Wind Task 29 (MexNext), IEA Wind Task 30 (OC5), &or Task 31 (WakeBench) or should new collaborative(s) be initiated?
    - Future work can be contained in existing (extended) annexes
    - Strong need for coordination of work between Tasks
    - A steering group is proposed

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Summary of OC6 Discussions

Amy Robertson

September 8, 2017

Focus Areas

- Inclusion of higher-fidelity models to better understand deficiencies in engineering-level hydrodynamic models
- Validate a model of a real, full-scale offshore wind turbine (preferably floating)
- Define more focused validation objectives
  - Specific to offshore wind systems – not covered by land-based wind or oil & gas
- Determine experimental uncertainty, and try to reduce it as much as possible.

Larger Focus on Hydrodynamics

- Aerodynamics
  - Biased group – will open discussion to all members after meeting
  - Much uncertainty in aerodynamics in tank test environment
- Hydrodynamics of offshore wind systems different than other structures
  - Different size – applicability of modeling theory
  - Different design criteria – need more optimized, less costly, maybe higher-risk
  - Difference in which hydrodynamic load components dominate
  - Shallow water, flexible systems
- Soil/structure interaction another area of interest

PIRT – Fixed Bottom Offshore Wind System

Phenomena	Importance	Physics Und.	Model Adequacy	Validation Needs
Fluid Dynamics				
2D wave elev. variation in farm	L	M	L	L
Short-crested	M	H	M	H
Ability to model real spectra/directionality	M	M	M	M
Environment-Structure Interaction				
Multi-body flow interaction	M	M	L	H
Breaking/steep wave loads	H	M	L	H
VIV/VIM - substructure	L	L	L	H
Viscous load model	M	M	M	H
Member-level loads (incl concrete)	H	H	M	M
Wave current–body inter	M	M	L	L
Soil/structure interaction	H	M	L	H
Marine growth infl on loads	M	H	H	L
Multi-scale	H	M	H	H

PIRT – Floating Offshore Wind Systems

Phenomena	Importance	Physics Und.	Model Adequacy	Validation Needs
Fluid Dynamics				
Short-crested	M	H	M	H
Low-frequency wind spectra/coherence	H	M	L	H
Ability to model real spectra/directionality	M	M	M	M
Environment-Structure Interaction				
Nonlinear excitation – diff/sum/mean	H	M	M	H
Multi-body flow interaction	H	M	L	H
Breaking/steep wave loads	L	M	L	H
VIV/VIM - substructure	M	L	L	H
Viscous load model	H	M	M	H
Potential combined with viscous	H	M	M	H
Member-level loads (incl concrete)	H	H	L	M

PIRT – Floating Offshore Wind Systems

Phenomena	Importance	Physics Und.	Model Adequacy	Validation Needs
Environment-Structure Interaction				
Wave current–body inter	H	M	L	M
Nonlinear hydrostatics + FK	H	M	L	M
Influence of elasticity on motion	M	H	L	M
Aerodyn. applicability under motion	H	L	M	H
Marine growth infl on loads	L	H	H	L
Multi-scale	H	M	H	H
Sloshing (ballasting, holes)	H	M	L	H
Controls				
Negative damping from blade pitching	H	H	H	L
Moorings/Cables				
Seabed friction – mooring	H	H	M	L
Wave forcing – mooring loads	H	H	H	L
Line hysteresis (moor/cable)	H	M	M	L

*Coupled aero/hydro analysis desired as well

Data Sets

- Nautilus – semisubmersible – Tank Test – Jan 2018
- Stiesdal TetraSpar – 3 Tank Tests – different configurations
- Our own testing
  - MaRINET2 – OC5 Semi
  - UMaine W2 tank
- Heave plate tests
- Hybrid testing at Poly. Milano
- **Suggestions?**

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Collaboration

- Not a lot of overlap
- Would like to have interaction
- Suggest a yearly update meeting between the three projects

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