Report

EERA DeepWind'2018 Conference
17 – 19 January 2018

Radisson Blu Royal Garden Hotel, Trondheim

John Olav Tande (editor)
Report

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John Olav Tande (editor)

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ABSTRACT


Presentations include plenary sessions with broad appeal and parallel sessions on specific technical themes:

a) New turbine and generator technology
b) Grid connection and power system integration
c) Met-ocean conditions
d) Operations & maintenance
e) Installation & sub-structures
f) Wind farm optimization
g) Experimental Testing and Validation
h) Wind farm control systems

Plenary presentations include frontiers of science and technologies and strategic outlook. The presentations and further conference details are also available at the conference web page: https://www.sintef.no/projectweb/eera-deepwind

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<td>Nils Røkke, Chair, European Energy Research Alliance (EERA)</td>
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<tr>
<td>11.05</td>
<td>Panel debate, moderated by Prof Johan Hustad: the role of R&amp;I to maximize the economic attractiveness of offshore wind.</td>
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<td>Mitigation of Loads on Floating Offshore Wind Turbines through Advanced Control Strategies, D. Ward, Cranfield University</td>
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<td>Impact of the aerodynamic model on the modelling of the behaviour of a Floating Vertical Axis Wind Turbine, V.Leroy, LHEEA and INNOSEA</td>
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<td>16.10</td>
<td>Closing by Chair</td>
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<tr>
<td>18.00</td>
<td>We welcome you to an informal reception at Dokkhuset. A jazz club and concert venue in an old industrial building by the old dock. There will be a musical performance by Kristoffer Le and some light refreshments.</td>
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Thursday 18 January

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<td>North Seas Offshore Network: Challenges and its way forward, P. Härtel, Fraunhofer IWES</td>
<td>A Detached - Eddy - Simulation study: Proper - Orthogonal - Decomposition of the wake flow behind a model wind turbine, J. Göeßing, Technische Universität Berlin</td>
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Side event 1645-1845: Presentation of French research centres and companies involved in offshore wind energy
## Thursday 18 January

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<td>16. Supply chains for floating offshore wind substructures - a TLP example, H.Hartmann, University Rostock</td>
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<td>17. Critical Review of Floating Support Structures for Offshore Wind Farm Deployment, M Leimeister, REMS, Cranfield University</td>
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<td>18. Assessment of the state-of-the-art ULS design procedure for offshore wind turbine sub-structures, C. Hübner, Leibniz Univ Hannover</td>
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<td>24. ConstructionPossibilitiesforSerialProductionofMonolithicConcreteSparBuoyPlatforms, C. Molins, UPC-Barcelona Tech</td>
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27. Experimental validation of analytical wake and downstream turbine performance modelling, F. Polster, Technical University of Berlin

28. Reduce Order Model for the prediction of the aerodynamic lift around the NACA0015 airfoil, M.S. Siddiqui, NTNU

29. Fast divergence-conforming reduced orders models for flow, E. Fonn, SINTEF Digital

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30. Sensitivity analysis of the dynamic response of a floating wind turbine, R. Siavashi, University of Bergen


32. Parameter Estimation of Breaking Wave Load Model using Monte Carlo Simulation, S. Wang, DTU Wind Energy

33. Emulation of ReaTHM testing, L. Eliassen, SINTEF Ocean

34. Multiple degrees of freedom real-time actuation of aerodynamic loads in model testing of floating wind turbines using cable-driven parallel robots, V. Chabaud, NTNU/SINTEF Ocean

35. A 6DoF hydrodynamic model for real time implementation in hybrid testing, I. Bayati, Politecnico di Milano


37. Numerical modelling and validation of a semisubmersible floating offshore wind turbine under wind and wave misalignment, S.OH, ClassNK

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38. Impact on wind turbine loads from different down regulation control strategies, C. Galinos, DTU

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**Side event 1645-1845:** Presentation of French research centres and companies involved in offshore wind energy


19.00: Dinner
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<td>Chairs: Karl Merz, SINTEF Energi</td>
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<td>Prof Olimpo Anaya-Lara, Strathclyde University</td>
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<td>09.05</td>
<td><strong>F) Wind farm optimization</strong></td>
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<td>Chairs: Yngve Heggelund, CMR</td>
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<td>Henrik Bredmose, DTU Wind Energy</td>
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Scientific Committee and Conference Chairs

An international Scientific Committee is established with participants from leading institutes and universities. These include:

- Anaya-Lara, Olimpo, Strathclyde University
- Bredmose, Henrik, DTU
- Busmann, Hans-Gerd, Fraunhofer IWES
- Eecen, Peter, ECN
- Faulstich, Stefan, Fraunhofer IWES
- Furevik, Birgitte, R., Meteorologisk Institutt
- Heggelund, Yngve, CMR
- Jørgensen, Hans Ejsing, DTU
- Kvamsdal, Trond, NTNU
- Leithead, William, Strathclyde University
- Madsen, Peter Hauge, DTU
- Merz, Karl, SINTEF Energi
- Muskulus, Michael, NTNU
- Nielsen, Finn Gunnar, UiB
- Nygaard, Tor Anders, IFE
- Reuder, Joachim, UiB
- Robertson, Amy, NREL
- Rohrig, Kurt, Fraunhofer IWES
- Sempreviva, Anna Maria, CNR
- Tande, John Olav, SINTEF Energi
- Uhlen Kjetil, NTNU
- Van Wingerde, Arno, Fraunhofer IWES
- Van Bussel, Gerard, TU Delft
- Welte, Thomas, SINTEF Energi
- Wiggert, Marcel, Fraunhofer IWES
- Økland, Ole David, SINTEF Ocean

The Scientific Committee will review submissions and prepare the programme. Selection criteria are relevance, quality and originality.

The conference chairs were:

- John Olav Gjæver Tande, Chief scientist, SINTEF Energi AS
- Trond Kvamsdal, Professor NTNU
- Michael Muskulus, Professor NTNU
Opening session – Frontiers of Science and Technology

Opening note by chair

Alexandra Bech Gjørv, CEO, SINTEF

Jørn Scharling Holm, Technology Partnerships Manager, Ørsted

Hanne Wigum, Manager Renewable Technology, Statoil

Matthijs Soede, Research Programme Officer, EC

Aiden Cronin, ETIPwind

Nils Røkke, Chair, European Energy Research Alliance (EERA)
R&I IN OFFSHORE WIND
Alexandra Bech Gjørv, CEO, SINTEF
EERA DeepWind, Trondheim, Jan 17, 2018

One of Europe’s largest independent research organisations
- 2000 Employees
- 75 Nationalities
- 4000 Customers
- NOK 3.1 billion Revenues
- NOK 450 MILL International sales

Major participant in EU research programs
- Participate in 133 projects, with a project volume of € 1371 mill.
- Coordinate 37 projects with a project volume of € 201 mill.
- SINTEF research funding from EU: € 87 mill.

Partnership with NTNU
- Strategic and operational cooperation since 1950
- Joint use of laboratories and equipment
- Cooperation covers research projects, research centers and teaching
Close working relationships generate innovation and high quality

Hywind model test (2005)

Laboratories and test facilities

- World-leading within a range of technology areas
- From nano and micro electronics to high voltage and ocean laboratories

Bold visions – in 2006

- Support structures
- Marine operations
- Materials
- Grid connection
- System integration
- Energy storage
- Asset management
- Wind farm control
- Digitalization

Offshore wind research priorities
NOWITECH has 40 innovations in progress

Potential value of innovations

NPV: > 5000 MEUR*

* Result from analysis carried out by Impello Management AS for a subset of innovations by NOWITECH. NPV is calculated as socio-economic value of applying the innovations to a share of new offshore wind farms expected in Europe until 2030.

Wind goes digital
ØRSTED WIND POWER WAY OF WORKING WITH RD&D

Trondheim, 17th January 2018
Jørn Scharten Høiby
Technology Partnership Manager

Ørsted R&D strategy and types of collaboration

1. R&D strategy review
2. Project outcome, scope and impact
3. Project management efficiency and administration
4. Confidentiality and IPR
5. Competence match
6. Internal / external funding

Internal R&D projects
Small collaborative R&D projects
Large R&D consortium projects
Joint Industry Projects

R&D Programmes

Ørsted R&D strategy and types of collaboration

- building competences leading to improved R&D

Ørsted’s overview of levers for CoE reduction

Multiple levers to drive down cost in offshore wind power

Scale
- Turbine size
- Site size
- Vessel size

Innovation
- Foundation
- Electrical infrastructure
- Transition from single supply to multiple global suppliers

Industrialisation
- Innovation
- Foundation
- Electrical infrastructure
- Transition from single supply to multiple global suppliers

Rapid technological development
Wind turbine rotor diameter, year of commissioning

Ørsted’s R&D Programme

R&D Strategy
- organised in 5 Roadmaps

Roadmap 1
Wind & Waves
- Substation design
- Array and export cables layout and installation
- Grid simulations
- Grid connection
- Ancillary services

Roadmap 2
Foundations, Geoscience and Marine
- Geotechnical survey methods
- Monopile/jacket design methods
- Foundations fabrication
- Underwater noise damping
- Corrosion protection

Roadmap 3
Electrical Infrastructure
- Substation design
- HV and export cables layout and installation
- Grid simulations
- Grid connection
- Auxiliary services

Roadmap 4
WTG O&M
- Component reliability
- New component
- New O&M inspection and replacement methods

Roadmap 5
Logistics
- Geotechnical survey methods
- Monopile/jacket design methods
- Soil-structure interaction
- Underwater noise damping
- Corrosion protection

Objectives
Enable the pipeline, CoE reduction, Risk reduction, HSE performance, Design standard improvements and competence development

 Ørsted R&D strategy and types of collaboration

- building competences leading to improved R&D
Six research areas - Focusing on everything but the turbine, representing roughly 70% of offshore wind energy costs

- Development
- Construction
- Finance
- Installation
- Foundations
- Electrical
- Turbine

LCOE Breakdown

Source: Navigant

Example on joint demonstration and commercialisation - Carbon Trust OWA

From basic research to commercial deployment - how, who, what...

Innovation is critical to delivering cost reduction and building supply chain capability

- Balance of support required across technology readiness levels (TRL)
- Forging links between industry and academia can maximise market penetration of new technologies
- Greater information and data sharing can accelerate technology innovation

IEA - Renewable Energy Technology Deployment, published in March 2017

Thank you for your attention
Statoil’s journey in offshore wind
Hanne Wigum-Manager R&D Renewable Technology- Statoil
EERA DeepWind’18

Sharpened strategy: Building a profitable new energy business

INDUSTRIAL APPROACH
• Leverage core competence
• Scale & technology reduce costs
• Access to long-term projects

VALUE DRIVEN
• From subsidies to markets
• Cash flow resilience

GROWTH OPPORTUNITIES
• 15-25% of capex in 2030
• Offshore wind and other options
• Low-carbon solutions

Rapid expansion within offshore wind

Playing to our strengths

Attractive market

Vast potential for floating offshore wind

Energy transition is a journey...

TROLL 1995    SNØHVIT 2007    HYWIND 2017

Energy transition is a journey...

2016      2017-20      2020-25

~ 500
750 ~
1500 ~

Indicative for offshore wind projects

Indicative, based on potential future corporate portfolio.

2016

USD million

2019

Dudgeon

¹

Indicative for offshore wind projects

2019

3 x 1.2 GW
5.3 GW

Dudgeon

Sheringham Shoal

Hywind demo

Dudgeon

Dogger Bank

Hywind pilot

Hywind large scale

North West Europe

In operation
In operation
In operation
In operation
Consented

2.3 MW
317 MW
423 MW
30 MW
3 x 1.2 GW

2019

317 MW
205.1
205.1
2017
1899

385 MW

2019

3 x 1.2 GW
5.3 GW

Arkona

385 MW

In development

2024 +

New York United States

East Coast

Attractive market

Playing to our strengths

2024 +

US West Coast

Japan

Scotland/Ireland

The big four

Vast potential for floating offshore wind

Size of the prize
32 GW in 2040

Expected LCoE
40 – 60 €/MWh by 2030

The big four

US West Coast

Japan

France

Scotland/Ireland

Utility scale

BIG CITIES

ISLANDS

OIL AND GAS

Vast potential for floating offshore wind
Next step for Hywind - lead floating wind to industrial scale

- Cost
  - Optimise wind energy
  - Scale

- Deployment
  - Scalability critical for market success
  - 2030 target
  - Demo/Pilot park

- Concept development
  - Next: Large parks
  - Design for scale and weight
  - Proprietary motion controller
  - Site selection and park layout
  - Installation and maintenance

- Technology development focused on:
  - Hywind cost roadmap
  - 2030 Today
  - WTG
  - Electrical infrastructure
  - Substructure
  - Logistics
  - Mooring
  - Installation

- 2023 LCOE target
  - 40-60 €/MWh

- 2030 Capex/MW
  - 50%

Leverage three pillars for Hywind cost reduction

- Extract and systemise learnings from projects

Targeted technology development to support a growing business

- Wind resource
  - Global wind resource
  - Measurement technologies
  - Wind conditions, turbulence and wake

- Energy harvesting
  - New concepts for assembly and heavy lift operations

- Structural design and production
  - Methods and software for optimised design

- WTG O&M
  - New concepts for assembly and heavy lift operations

- Marine operations and logistics
  - O&M data analysis
  - Condition based maintenance

What colour do you dream in?
January
- Investment in offshore wind reaches a new high, according to Bloomberg New Energy Finance (BNEF), at $29.9 billion in 20X6, 40% up on the previous year. But total investment in clean energy falls 18% year-on-year to $287.5 billion.
- MHI Vestas unveils a 9MW evolution of its V164 offshore turbine. It would grow again within a few months.
- The UK Court of Appeal dismisses Wobben Properties’ claim that Siemens infringed a storm-control technology patent developed for Enercon.

February
- Nordex takes control of Danish blade designer and manufacturer SSP Technology, putting the acquisition to good use with the announcement of a 4.0-4.5MW turbine with a 149-metre rotor diameter later in the year.
- Saudi Arabia announces a tender for 400MW of wind and 300MW of solar PV.
- FTI Consulting releases preliminary findings of its Global Wind Market Upgrade 2016, showing Vestas as the world’s top OEM. Previous leader, Goldwind, drops to third behind GE as a result of the slowing Chinese market.
- Siemens Wind Power confirms it will close its blade factory in Engesvang, west Denmark, due to “significant changes in the global wind-power market”. The 430 jobs lost are on top of the 150 to be cut from another of its blade plants in Aalborg in the north of the country.
- GE Renewable Energy appoints Anne McEntee to lead its servicing business, while Peter McCabe takes on her old role as onshore wind chief executive.

March
- Vestas installs a new tower design using support cables to spread the increased load of taller turbines. The concept enables turbines to be installed on narrower towers, cutting manufacturing and transport

The industry’s biggest merger, the first serious floating offshore project, the rise in power ratings and hub heights... David Weston and Craig Richard pick out the highlights from Windpower Monthly's coverage of 2017.
GLOBAL REVIEW OF THE YEAR

Siemens installs a prototype of its new low-wind SWT-3.15-142 turbine at Drantum, central Denmark. It will be available with hub heights of up to 165 metres for a tip height of around 234 metres.

Nordex CEO Lars Bondo Krogsgaard resigns after the company reduced its forecast for the 2017 and 2018 financial years. Former Acciona Wind Power chief Jose Luis Blanco steps in.

Senvion cuts 780 jobs with production sites at Trampe and Husum in Germany taking most of the losses. The company predicts the global move to competitive tendering will create short-term pricing pressures as it announces a two-year "transition" to adjust to market demands.

April

The long-anticipated merger of Siemens and Gamesa comes into effect, creating a company with 75GW of installed wind capacity across 90 countries, and 27,000 employees. Combined annual revenue stands at €11 billion, and the company has an order backlog worth €21 billion. Windpower Monthly gets exclusive access to two new product series. Enercon’s 4.2MW EP4 platform, the first of several 4MW-plus onshore turbines now on the market, offers an industry-first 30-year design life. Vestas upgrades its best-selling V10-2MW turbine with rotor diameters of 116 and 120 metres to boost annual energy production. Developers Dong Energy and EnBW are awarded licences for four projects in Germany’s first competitive auction, with three sites to be built without subsidy. Both companies have operating offshore sites in the country already.

May

Senvion lets slip at the AWEA Windpower 2017 event in California that it is working towards a 10MW-plus offshore wind turbine. No specifics were forthcoming in London, but the Senvion-led Realcoe collaboration...
would apply for EU funding to speed up development in November. Wind projects are allocated 2,979MW of the 3GW available in Spain’s second renewables auction, underlining renewed interest in the country’s wind market. All winning bids are made with “full discount” — meaning operators accept zero subsidy and will receive only the wholesale price for electricity generated. Goldwind acquires the up-to-530MW Stockyard Hill project in Victoria, Australia, from Origin Energy, and agrees to sell the power back to the utility. The PPA is believed to be the largest wind deal to date in Australia.

June
- Vestas shifts its 3MW platform into the rapidly growing 4MW class, unveiling three models with a power rating of up to 4.2MW. The low-wind V150 boasts the largest rotor diameter yet seen onshore, while the high-wind V117 takes the turbine into typhoon territory for the first time. MHI Vestas unveils an upgrade to its V164 offshore turbine, taking rated capacity up to 9.5MW. It is later specified for the UK’s 950MW Moray East and 860MW Triton Knoll projects in the North Sea.
- In a first step to align Adwen with its new parent company, Siemens Gamesa Renewable Energy (SGRE), two separate legal entities are to be created: Adwen Operations, which will focus on four German projects equipped with its 5MW (formerly Areva) turbines, and French Pipeline, to develop 1.5GW of French offshore sites up to the start of construction. Three months later SGRE stops production plan for Adwen’s 8MW offshore turbine. Vestas is announced as preferred turbine supplier for 1GW of projects won by developer Fortum in the Russian tender. Fortum will develop its capacity alongside Russian energy company Rusnano, spread across 26 projects between 2018 and 2022.

July
- Enercon is set to refurbish up to 1,200 turbines in India, following the conclusion of a decade-long legal dispute with former joint venture Wind World India. The firm says some 860MW of its turbines could be re-activated and updated after its ten-year absence from the world’s fourth largest market, where Enercon has roughly 6,700 turbines installed. Elsewhere in India, the country’s 1GW power auction receives 2.6GW of bids, following the success of its first auction earlier in the year. The results, announced later in October, will see prices fall to a new low of INR 2.64/kWh ($0.04/kWh).
- In Europe, developer Vattenfall reshuffles its wind unit, splitting it in three – onshore, offshore, and solar – with storage. Vattenfall Wind CEO Gunnar Groebel says the move “creates a lean business model ... that can respond to different markets”.
- Nordex’s record-breaking 230-metre high turbine in south-west Germany produces more than 9GWh of electricity in its first year of operation.

August
- In a Windpower Monthly exclusive, Enercon unveils a new modular approach it is taking with its 3MW platform. The move is in response to the shift to auction-based systems around the world forcing margins to be compressed, meaning Enercon was losing out to cheaper rivals. All future Enercon turbines will be based on the new design approach and will meet IEC wind class demands exactly, rather than exceed them, the manufacturer says. Rival manufacturer SGRE announces it is making up to 600 further job cuts at its...
blade plant in Aalborg. The move comes just eight months after an initial 580 jobs were cut, prior to the merger. GE Renewable Energy files a dispute in California claiming market leader Vestas was in breach of its zero-voltage ride-through (ZVRT) technology patent. MHI Vestas launches an investigation after its 9.5MW prototype in Osterild, Denmark, catches fire. The subsequent examination finds a component “damaged during installation” was the cause. MHI Vestas says the part is “unique to a prototype environment” and that the rollout of the turbine will not be affected. Gamesa also suffers a fire at a 13-year-old turbine in Japan. Several local news outlets show a burned-out nacelle.

September
GE Renewable Energy continues the year’s big technological trend, with the launch of a new 4.8MW onshore turbine for low- to medium-wind markets like Germany, the Netherlands, Turkey, Chile and Australia. The new model features a 158-metre rotor and will offer the industry’s largest annual energy production, GE claims. Vestas confirms it is working with Elon Musk’s Tesla on energy storage solutions. Vestas is looking to increase its involvement in integrating wind and storage solutions and has been working on a number of small-scale projects over recent years. The year is shaping up to be a difficult one for the leading manufacturers. Nordex announces a €45 million cost-cutting programme, which would also see up to 500 jobs lost, mostly in Germany. Vestas, meanwhile, signs a deal to set up a manufacturing hub in Russia, on the back of potentially winning a 1GW deal with Finnish developer Fortum and its joint venture partner Rusnano, which won the majority of capacity up for grabs in June’s 1.65GW tender.

October
Andreas Nauen is back as a leading light at a major manufacturer. The former Senvion CEO is appointed to lead SGRE’s offshore division, following the departure of Michael Hannibal. In a small reshuffle at SGRE, driven by poor financial forecasts, Miguel Angel Lopez is appointed as chief financial officer, replacing Andrew Hall, and Jürgen Bartl replaces Jose Antonio Cortajarena as general secretary. Max Bögli breaks its own record for the tallest onshore turbine in the world, reaching a tip height of 246.5 metres. The 3.4MW GE turbine, installed near Stuttgart, south-west Germany, incorporates a 40-metre high water reservoir at the base of the tower as part of a pumped-hydro storage solution. October marks the birth of floating offshore wind. Statoil’s 30MW Hywind Scotland project begins production, while Ideol inaugurates its ring-shaped pool-dampening floater, topped with a Vestas 2MW turbine, in the port of St-Nazaire, France. Ideol CEO Paul de la Guérivière describes the moment as a “turning point” in the floating wind sector.

November
Turbine launches at WindEurope’s conference and exhibition in Amsterdam include SGRE’s 8MW direct-drive offshore model, equipped with a 167-metre rotor and a power-mode option to increase output to 9MW. SGRE also launches a new 4MW geared platform with one model per wind-speed class. Envision reveals three new onshore models including a 4.5MW machine. Leading Indian manufacturer Suzlon showcases a textbook reversal of fortune for many turbine makers by recording a 56% year-on-year fall in income in Q3, due to the market uncertainty in the subcontinent. The firm reported a profit of INR 681 million ($10 million) in the third quarter — a 72.07% reduction year-on-year.

December
Germany’s energy regulator devises a plan to avoid some of the unintended consequences of its new onshore auction system, setting a maximum bid price of €63/MWh in 2018, after 2017’s tenders pushed prices below current generation costs. Argentina’s wind power gathers pace with eight wind farms totalling almost 666MW awarded PPAs in the second renewables tender at an average price of $41.23/MWh.
What are ETIPs?

European Technology and Innovation Platforms are industry-led stakeholder fora recognised by the European Commission.

**Goals**

- Drive innovation, knowledge transfer and European competitiveness
- Develop research and innovation agendas and roadmaps for action at EU and national levels

Many companies are in Norway because of its R&D support schemes – EU needs to emulate this success.

Why is ETIP needed?

- Give EU direction in what R&I areas should be supported
- A forum where industry, research bodies and academia can meet and forge a common vision of the future
- Advisory group of CTO’s now have a forum to discuss what should be done together
- Steering Committee is the workhorse that gets stuff done.
- The key raw material for the continued success of the EU Wind industry is well trained scientists and engineers – ETIPWind can help ensure this!

Objectives of the SRIA – update in 2018

- Reduce costs
- Facilitate system integration
- Reinforce European technological leadership
- Ensure first-class human resources
Some of what has happened
When industry meets well trained creative brains

- Vinderby 11x 450 kw erected in 11 days 1991
- Middelgrunden 20 x 2MW in 2000 - iconic
- Horns Rev 1 with 80 x 2MW first big offshore park
- BTM UK offshore report.
- A2SEA installer – Coaster with legs
- Hywind – 2.3MW floater – Statoil a first floater off Norway called “crazy” now Hywind 2 in Scotland
- London Array Phase 1 630MW - huge
- Ørsted q European world champion in wind

Scope of the discussion

Technology

What needs to happen

- Costs needs to continue to drop
  - Structures need industrialization
  - Cables
  - Installation and maintainence
  - Robotics
- Offshore wind is bulk electricity – challenges
  - Large scale storage
  - Watershed – Grid has to become renewable friendly not the opposite

What has and is happening in offshore wind?
All wind actors need to

• Drive digitalization
• Drive storage
• Drive cyber security
• Drive and enable the electrification of society
• Provide a credible back bone to climate change challenged electricity system

If you do cannot drive you are left behind

In weather terms offshore is coming onshore with increased flooding and marinisation of land

Thank you
www.etipwind.eu
Co-ordinating energy research for a low carbon Europe

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<thead>
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<th>Country membership by joint programme</th>
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<th>Mission Innovation Challenges</th>
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<td>4 out of 7</td>
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Most influential energy research community in EU & globally

<table>
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<th>50,000+ Experts</th>
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<tr>
<th>250+ Organisations</th>
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<th>29 Countries</th>
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<th>35% Cross-cutting &amp; societal challenges</th>
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<th>All 10 SET Key Actions</th>
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<th>All 9 ETIPs and other platforms</th>
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EERA JP WIND structure and sub-programmes

- Joint Programme Coordinator: DTU Wind Energy
  - Wind Conditions: Coordinated by DTU, Denmark. Aerodynamics: Coordinated by ECN, the Netherlands.
  - Wind Integration – economic and social aspects: Coordinated by DTU, Denmark.

- 14 Full Participants and 36 Associate Participants
- Election of new Management Board in March 2018

Funding for EERA activities

- National projects (competitive)
- In-kind (institutional)
- EU calls (H2020) e.g. CSA, IRP, ECRIs
- Other types of Joint Programming e.g. ERANET+, Berlin Model

- Coordination of research activities
- Collaboration for common R&I agendas
- Co-creation of new joint R&I projects and programmes

Total budget: €9.8 million

- €6 million for 3 Core Projects (each linked to national projects)
  - Offshore
  - Structural Reliability
  - Integration
- 4 M EUR for CSA
  - Mobility
  - Research Infrastructure
  - Secretariat, management
  - Access to data

Not all EERA Wind members directly involved (but CSA-part benefits all)
Ends in April 2018

Pilot programme on cold climate (VIT)
Co-ordinating Energy Research for a Low Carbon Europe
A1) New turbine and generator technology

Lightweight design of the INNWIND.EU and AVATAR rotors through multi-disciplinary optimization algorithms, A.Croce, Politecnico di Milano

Initial Design of a 12 MW Floating Offshore Wind Turbine, P.T.Dam, University of Ulsan

Performance Assessment of a High Definition Modular Multilevel Converter for Offshore Wind Turbines, R.E.Torres-Olguín, SINTEF Energi

Mitigation of Loads on Floating Offshore Wind Turbines through Advanced Control Strategies, D. Ward, Cranfield University
Lightweight design of the INNWIND.EU and AVATAR rotors through multi-disciplinary optimization algorithms

A. Croce[1,2], L. Sartori[1,2], P. Bortolotti[1], C. L. Bottasso[1,2]

[1] Department of Aerospace Science and Technology, Politecnico di Milano, Italy
[2] Technische Universität München, Germany

EERA DeepWind 2018, 17 January 2018, Trondheim

Outline

- Background
- Multi-disciplinary design algorithms for wind turbines
  - Cp-Max: a modular design framework
  - Passive load-alleviation techniques
  - Applications
    - Lightweight redesign of the INNWIND.EU rotor
    - Lightweight redesign of the AVATAR rotor
  - Conclusions

Background

- Large rotors for 10+ MW wind turbines:
  - Strong aero-servo-elastic couplings
  - High mass and loads due to slender and flexible components
- Load-mitigation:
  - Passive and active techniques
  - Reduced loads on blades and fixed infrastructure
  - Impact on the AEP
- MDAOs help the design process:
  - High-fidelity models plus dedicated optimization methods
  - Automatic management of preliminary/detailed design of WTs
  - Trade-offs and cost-oriented studies

Cp-Max: a modular design framework

Macro Optimization: min CoE
Opt. variables: Rotor diameter, turbine height, cone, uplift, blade shape
parameters e, x, y, f
Constraints: max loads, max turbine height

Aerodynamic Optimization: max AEP
Opt. variables: chord and twist distributions, airfoil positions
Constraints: max chord, max blade tip speed, e, x, y, f

Control synthesis
Pre-bend optimization
Load calculation
Acoustic analysis
CoE model

Structural Optimization: min ICC
Opt. variables: Thickness of blade structural components, tower wall thickness and
diameters, composite material parameters
Constraints: stress, strain, fatigue damage for
blade, hub, tower and support structure, max tip displacement, natural frequencies

Until converged
3D FEM verification

Holistic Design of Wind Turbines

Classical approach to design (weak) loops between specialist groups

There is a need for multi-disciplinary optimization tools, which must:

- Be fast (hours/days) (on standard hardware)
- Provide solutions in all areas (aerodynamics, structures, controls, sub-systems)
- Account ab-initio for all complex couplings (no fixes a posteriori)
- Use fully-integrated tools (manual intervention very limited)

These tools will never replace the experienced designer! … but would greatly speed-up design,
explore exploration/knowledge of design space.
**Multibody Dynamics Technology**

**Cp-Lambda highlights:**
- Geometrically exact composite-beam models
- Fully populated 6x6 stiffness (aerelastic couplings)
- Generic topology (Cartesian coordinates + Lagrange multipliers)
- Hydrodynamic loads
- Rigid body - Cosmetically exact beam
- Flexibale joint - Actuator

---

**Manufactured Blades**

- 2MW - 45m (WATT-Gurti)
- 300kW - 16m (Italttech-Gurit-Euros)
- 700kW - 24m (ETA-Gurti-ECN)
- 100kW - 10m (ETA)

---

**Passive load-alleviation techniques (i)**

- Fiber-induced Bend/Twist Coupling (F-BTC)
  - Rotation of the laminae of composite fabrics
  - Increased extra-diagonal stiffness $K_{PLA/YOR}$
  - Load mitigation due to induced torsion

---

**Passive load-alleviation techniques (ii)**

- Offset-induced Bend/Twist Coupling (O-BTC)
  - Geometric offset between spar caps
  - Increased extra-diagonal stiffness $K_{PLA/YOR}$
  - Load mitigation due to induced sweep
### Reference wind turbines

<table>
<thead>
<tr>
<th>INNWIND.EU</th>
<th>AVATAR</th>
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<tbody>
<tr>
<td><strong>Design philosophy</strong></td>
<td>Classic, max(Cp)</td>
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<td><strong>Rated power (MW)</strong></td>
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<tr>
<td><strong>IRC Class [-]</strong></td>
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<td><strong>Blade length [m]</strong></td>
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<td><strong>Rotor diameter [m]</strong></td>
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<td><strong>Hub height [m]</strong></td>
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<tr>
<td><strong>Nacelle up-tilt [deg]</strong></td>
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<tr>
<td><strong>Rotor pre-cone [deg]</strong></td>
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<td><strong>Rotor speed [RPM]</strong></td>
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<tr>
<td><strong>Tower mass [kg]</strong></td>
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</table>

**Lightweight redesign of the AVATAR rotor**

**Parametric lightweight redesign**

- Parametric F-BTC (carbon spar caps) + pitch re-scheduling

**Setup**

- Classic WTs operate at Optimal $C_p$ ($a = 1/3$)
- By operating at Lower Induction, one could trade some efficiency to achieve lower loads
- Impact on COE and support structure is still not very well studied

**Goals:**
- Apply F-BTC to mitigate loads
- Redesign rotor to minimize the ICC
- Optimize collective pitch to increase AEP

**Cp-Max modules:**
- Structural Design Submodule (SDS)
- Finite Element Model
- Stability analysis tool

**Design constraints:**
- Same radius of the Baseline
- Same planform of the Baseline

**Note:** all rotors satisfy the same design constraints!

**Results:**
- All loads reduced. Best reduction for F-BTC of 5°
- AEP restored by optimal pitch scheduling
- COE reduction for all the parametric solutions

**Lightweight redesign of the AVATAR rotor**

**Final comparison**

- Ultimate loads
- Fatigue loads

Reference:

Conclusions

Remarks
- Several completed and ongoing activities about aero-structural rotor tailoring
- Application of load mitigation techniques to 10 MW concepts
- Important loads reduction (on hub and tower base)
- AEP losses could be limited by:
  - Elongating the blade (Optimal-Cp design)
  - Optimizing the collective pitch (Low-Induction design)
- Automated design procedures can help in identifying the best trade-offs

Outlook
- Application of additional load mitigation techniques (flap, VGs)
- Assessment of the effect of load alleviation techniques on the rotor stability
- Include airfoil shapes in the optimization loop
- Add module to analyze and design the support structure

Lightweight redesign of the INNWIND.EU rotor

Setup

Goals:
- Apply F-BTC, O-BTC and IPC to mitigate loads
- Redesign rotor to optimize COE

Cp-Max modules:
- Aerodynamic Design Submodule (ADS)
- Structural Design Submodule (SDS)

Design constraints:
- Same hub thrust of the Baseline
- All loads at Hub, Tower Base < 1.10 than the Baseline
- Same rotor solidity of the Baseline

Results:
- Longer blade
- Larger AEP
- Same thrust
- Loads at HC, TB do not exceed 10% more than Baseline

| | Baseline 120m | 10 MW | \% variation |
|--------------------------|--------------------------|--------------------------|
| Diameter [m] | 110 | 140 | +5 % |
| SC fiber angle [deg] | 0 | 5 | - |
| SC offset [mm] | 0 | 10 | - |
| Max chord [mm] | 63 | 63 | 0 % |
| Blade mass [ton] | 42 | 46 | +16.5 % |
| AEP [GWh] | 46.4 | 46.8 | +0.8 % |
| COE [€/MWh] | 74.8 | 72.8 | -2.6 % |
Initial Design of a 12 MW Floating Offshore Wind Turbine

Pham Thanh Dam, Byoungcheon Seo, Junbae Kim, Hyunjo Jung, Dongja Kim and Hyunkyoung Shin

School of Naval Architecture & Ocean Engineering, University of Ulsan, Korea
EERA DeepWind’2018, JAN. 17, 2018, Trondheim, Norway

Outline

- 12MW FOWT design
- Numerical Simulation
- Design Load Cases
- Results
- Conclusion

12MW FOWT Design

Outline

12MW Blade Scale ratio

$$P = C_p \times \frac{1}{2} \rho A V^3$$

$$\lambda_{Blade} = \frac{P_{12MW}}{P_{5MW}} = 1.549$$

12MW Carbon blades

- 61.5 (m) 5MW glass blade : 17.7 ton
  - 95.28 (m) 12MW glass blade : 62.6 ton (Too heavy)
  - 95.28 (m) 12MW carbon (sparcap) blade : 42.7 ton

<table>
<thead>
<tr>
<th>Scale-up blade properties(deflection)</th>
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<tr>
<td>N.</td>
</tr>
<tr>
<td>CFRP</td>
</tr>
<tr>
<td>GFRP</td>
</tr>
<tr>
<td>N.F. [Hz]</td>
</tr>
<tr>
<td>12MW Blade</td>
</tr>
<tr>
<td>5MW Blade</td>
</tr>
</tbody>
</table>
| P1 : Power output (W)
  P : Power output (W)
  \rho : Air density (1.225 kg/m³)
  A : Averaged swept area (m²)
  V : Wind speed (m/s)

12MW Super conductor synchronous generator

- Modularized generator
- Rotor body
- Stator body
- Stator teeth
- Stator coil
- Cooling pipes
- Flexible shaft
- HTS one pole module
- Flux pump exciter

12MW Tower properties
- Scale up using offshore tower from OC4 definition
- 12MW "Material : steel, Height : 110.88 m, Weight : 781.964 ton (scale-up)"
- Beam deflection \( \delta = \frac{7FL^3}{3EI} \)
- Scale-up tower properties
  \[ T = C \cdot \frac{12L_s^4}{S_G^4} \]
- Tower scale ratio
  \[ \lambda_s = \frac{E_{12}L_s^4}{S_{12}^4} = 1.482 \]

<table>
<thead>
<tr>
<th>Rating</th>
<th>5 MW</th>
<th>12 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Orientation</td>
<td>Upwind, 3 Blades</td>
<td>Upwind, 3 Blades</td>
</tr>
<tr>
<td>Control</td>
<td>Variable Speed, Collective Pitch</td>
<td>Variable Speed, Collective Pitch</td>
</tr>
<tr>
<td>Drive train</td>
<td>High Speed, Multiple-Stage Gearbox</td>
<td>Low Speed, Direct Drive (gearless)</td>
</tr>
<tr>
<td>Rotor Hub Diameter</td>
<td>126 m, 5 m</td>
<td>195.2 m, 4.64 m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>90 m</td>
<td>118 m</td>
</tr>
<tr>
<td>Cut-in, Rated, Cut-out Wind Speed</td>
<td>3 m/s, 11.4 m/s, 25 m/s</td>
<td>3 m/s, 11.2 m/s, 25 m/s</td>
</tr>
<tr>
<td>Overhang, Shaft Tilt, Pre-cone</td>
<td>5 m, 5°, 2.5°</td>
<td>7.78 m, 5°, 3°</td>
</tr>
<tr>
<td>Rotor Mass</td>
<td>110,000 kg</td>
<td>297,660 kg</td>
</tr>
<tr>
<td>Nacelle Mass</td>
<td>240,000 kg</td>
<td>400,000 kg (Target)</td>
</tr>
<tr>
<td>Tower Mass (for offshore)</td>
<td>249,718 kg</td>
<td>735,066 kg</td>
</tr>
</tbody>
</table>

12MW Campbell diagram (Tower Redesign)
- Tower Length : 104.23 m
- Tower Mass : 735,066 kg
- Rotor speed : 8.25 rpm
- Rotor 3P-Excitation : 0.4125
- Tower 1st Side to Side Natural Frequency : 0.4337
- Tower Length : 104.23 m
- Tower Mass : 735,066 kg
- Rotor speed : 8.25 rpm
- Rotor 3P-Excitation : 0.4125
- Tower 1st Side to Side Natural Frequency : 0.4337

OC4 semi-submersible models
- Original OC4 Semi Offset column
- NTMU optimal OC4 semi Offset column
- ONU semi UOU modified Offset column
- Filling ballast water in base column tanks (water level is on the top of air vent pipe) will reduce the difference of pressure between inside and outside footing ballast tank

Design Summary

- Scale up using offshore tower from OC4 definition
- 12MW "Material : steel, Height : 110.88 m, Weight : 781.964 ton (scale-up)"
- Beam deflection \( \delta = \frac{7FL^3}{3EI} \)
- Scale-up tower properties
  \[ T = C \cdot \frac{12L_s^4}{S_G^4} \]
- Tower scale ratio
  \[ \lambda_s = \frac{E_{12}L_s^4}{S_{12}^4} = 1.482 \]
**Principle of platform upscaling**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Original</th>
<th>Upgraded OC4</th>
<th>NTNU Optimise</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform steel ton</td>
<td></td>
<td></td>
<td>9,525</td>
<td>8,822</td>
<td>8,661</td>
<td>8,168</td>
</tr>
<tr>
<td>Difference%</td>
<td></td>
<td></td>
<td>0.0</td>
<td>7.4</td>
<td>9.1</td>
<td>14.0</td>
</tr>
</tbody>
</table>

**Checking structure strength**

Calculate equivalent stress for the inner wall of bottom point of upper column:

\[ \sigma_{eq} = \sqrt{\frac{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \nu (\sigma_x + \sigma_y + \sigma_z)}{3}} \]

Pressure checking point: inner wall of upper column at lowest position.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Original</th>
<th>Upgraded OC4</th>
<th>NTNU Optimise</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform steel ton</td>
<td></td>
<td></td>
<td>47.6</td>
<td>50.1</td>
<td>50.1</td>
<td>48.9</td>
</tr>
<tr>
<td>Steel AH36 (0–50mm)</td>
<td></td>
<td>Field stress</td>
<td>940</td>
<td>940</td>
<td>940</td>
<td>940</td>
</tr>
<tr>
<td>Steel SS40 (0–50mm)</td>
<td></td>
<td>Field stress</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td>245</td>
</tr>
</tbody>
</table>

**12 MW Stability analysis**

12 MW FOWT Platform modification based on:
- Reduced main column elevation above MSL to 10 m
- Reduced offset column elevation above MSL to 13 m (the same as OC4 semi-submersible model)
**Reference location: West of Barra - Scotland**

100m water depth

Main wind direction: SW

Source: JFSSD-‘10.1 Oceanographic and meteorological conditions for the design’ 2013

---

**Mooring line properties**

- **Water Depth**: m 100
- **Mooring Line Diameter (d)**: mm 162
- **Number of Mooring Lines**: 3
- **Angle Between Adjacent Lines**: deg 120
- **Depth to Anchors below SWL**: m 100
- **Fairleads Location above SWL**: m 10
- **Radius to Anchors from Platform Centerline**: m 80.5
- **Equivalent Mooring Line Extensional Stiffness EA**: N 2.360E+09
- **Minimum Breaking Load**: N 2.600E+07

---

**Mooring lines arrangement**

- **Main Wind direction**: SW

---

**PI controller**

- Results using FAST Linearization with frozen wake assumption

---

**Numerical Simulation**
Flow Diagram of UOU + FAST v8

Ocean Engineering Wide Tank Lab., Univ. of Ulsan

UOU in-house code

- Hydrodynamic coefficients need for numerical simulation in hydro part

Hydrodynamic in-house code modeling:
- Consider parts under water line
- Neglect pontoons and braces

- **UOU in-house code**
  3D panel method (BEM)
  Element: 4000

  **Output**
  1. Added mass coefficients
  2. Radiation Damping coefficients
  3. Wave Excitation Forces/Moments

Design Load Cases (1/2)

<table>
<thead>
<tr>
<th>DLC</th>
<th>Mean</th>
<th>Speed</th>
<th>Model</th>
<th>Height</th>
<th>Skeelization</th>
<th>Current</th>
<th>Control/Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLC1.1</td>
<td>10.00</td>
<td>8.30</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
<td>DLC2.1</td>
<td>External Load</td>
</tr>
<tr>
<td>DLC1.2</td>
<td>1.00</td>
<td>8.30</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
<td>DLC2.1</td>
<td>External Load</td>
</tr>
<tr>
<td>DLC1.6</td>
<td>10.00</td>
<td>8.30</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
<td>DLC2.1</td>
<td>External Load</td>
</tr>
<tr>
<td>DLC1.8</td>
<td>10.00</td>
<td>8.30</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
<td>DLC2.2</td>
<td>1-hour operation</td>
</tr>
<tr>
<td>DLC2.1</td>
<td>10.00</td>
<td>8.30</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
<td>DLC2.2</td>
<td>1-hour operation</td>
</tr>
</tbody>
</table>

Simulation time:
3-hour irregular waves (33 trials × 3 wave seed numbers)

Results

Wind Turbulence

BModes

Multi-Blade Transformation

CATIA

Modeling

MORHO6SHHG0RGHO +HLJKW 'LUHFWLRQ

Wind Data Files

Linearized Models

Reflecting Boundary Condition

UOU in-house code

Ocean Engineering Wide Tank Lab., Univ. of Ulsan

Flow Diagram of UOU + FAST v8

Ocean Engineering Wide Tank Lab., Univ. of Ulsan

Design Load Cases (2/2)

<table>
<thead>
<tr>
<th>DLC</th>
<th>Mean</th>
<th>Speed</th>
<th>Model</th>
<th>Height</th>
<th>Skeelization</th>
<th>Current</th>
<th>Control/Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLC1.1, DLC1.2, DLC1.6</td>
<td>10.00</td>
<td>8.30</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
<td>DLC2.2</td>
<td>1-hour operation</td>
</tr>
<tr>
<td>DLC6.1, DLC10.1</td>
<td>10.00</td>
<td>8.30</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
<td>DLC2.2</td>
<td>1-hour operation</td>
</tr>
<tr>
<td>DLC1.8</td>
<td>10.00</td>
<td>8.30</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
<td>DLC2.2</td>
<td>1-hour operation</td>
</tr>
</tbody>
</table>

Design Load Cases(DLCs)
Extreme motions of the FOWT in parked conditions

Maximum fairlead tensions in operation conditions DLC1.1

Maximum fairlead tensions in extreme conditions DLC1.3

Serviceability Limit States (SLS) during non-operational:
Max. tilt: 15 deg. [max. value]
Nacelle acceleration: 0.6g

Extreme motions of the FOWT in operation conditions

Serviceability Limit States (SLS) during operational:
Max. tilt: 10 deg.
Nacelle acceleration: 0.3g

Ratios of sea to land of absolute extreme values (all DLCs)
**DLC1.2 Fatigue analysis**

Comparison between sea and land wind turbine based on:
- The same wind conditions
- The same controller
- Root of blade $m=30$, ultimate load $L_{Ult}=4600\,\text{kN}$
- Tower base $m=4$, ultimate load $L_{Ult}=8000\,\text{kN}$

![](image1.png)

**Ratios of Sea to Land**

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Ratio of Sea to Land</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{R}{m}$</td>
<td>$\frac{R}{m}$</td>
</tr>
<tr>
<td>$\frac{F_{xc}}{m}$</td>
<td>$\frac{F_{xc}}{m}$</td>
</tr>
<tr>
<td>$\frac{F_{yc}}{m}$</td>
<td>$\frac{F_{yc}}{m}$</td>
</tr>
<tr>
<td>$\frac{T_{wBf}}{m}$</td>
<td>$\frac{T_{wBf}}{m}$</td>
</tr>
<tr>
<td>$\frac{T_{wBf}}{m}$</td>
<td>$\frac{T_{wBf}}{m}$</td>
</tr>
</tbody>
</table>

**Lifetime Damage Equivalent Load**

**DLC9.1 Motions of the FOWT after a mooring line loss**

Wind turbine trajectories after mooring line 2 was lost!

**Conclusion**

- A design of the 12 MW FOWT was suggested.
- Lighting wind turbine mass such as super conductor generator, carbon fiber blade, short tower drive a smaller platform scale ratio.
- Strong wave and high current speed has a significant effect to the design of mooring system.
- Mooring line provided in 2 segments with heavier segment at anchor side to avoid the lift up force at the anchor.
- Loads and displacements of blades and tower in sea are higher than those in land.
- Wind and wave misalignments have strong effects to nacelle side to side acceleration.

**Future work**

- Consider 2nd order wave loads
- Optimize mooring system

**THANK YOU!**

**ACKNOWLEDGMENTS**

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20154030200970 and No. 20142020103560).
Damping

Hydrodynamic coefficients (1/2)

Design process for a floating offshore wind turbine
Grid Integration of High Definition MMC

Raymundo E. Torres-Olguin†, Michael Smailes, ‡ Chong Ng‡, Jose Luis Dominguez-Garcia, Angela Perez, Igor Gabiola, Giuseppe Guidi†, Salvatore D’Arco†

†SINTEF Energy research
‡Offshore Renewable Energy Catapult
Catalonia institute for energy research IREC
Tecnalia

Presenter: Raymundo E. Torres-Olguin

Introduction

• MMC is emerging topology for offshore wind substations due to its black start capabilities, low Total Harmonic Distortion (THD) and high efficiency.
• The MMC uses a stack of identical modules.
• The multiple voltage steps make the MMC being capable of producing very small harmonic content.

Content

• Introduction to the High Definition Modular Multilevel Converter
• Joint Experiments organized by IRP Wind
• HD-MMC on the performance in 3 phase converter+ high level control
• Concluding remarks
Joint Experiments within IRPWind

• This work is part of the 2nd call for Joint Experiments organized within the Research Infrastructure WP of IRPWind.
• IRPWind is a European project, which it is aimed to foster better integration of European research activities in the field of wind energy research.
• In Europe, most large research facilities are being devoted to national activities that not necessarily matching the needs of Europe as a whole.
• The Joint Experiments has the objective of promoting alignment through joint experiments carried out in European research facilities and its effective use of resources.

Previous results (1st Joint experiments)
The figure shows switching events SE (efficiency) vs THD. C-MMC with PWM has the lowest THD but with the highest SE. C-MMC with NLM has the lowest SE, but the highest THD. HD-MMC is a good trade-off between THD and efficiency.

Joint Experiments within IRPWind

• The HD-MMC control algorithm concept was successfully demonstrated in a project granted in the first IRPWind Joint Experiment call using a single phase, 18 module, half bridge MMC under controlled laboratory conditions
• The high level control was omitted to quantify the performance of the HD-MMC without any unnecessary complication. A simple RL load was used on the AC bus in place of an AC grid.

Previous experiment setup

<table>
<thead>
<tr>
<th>18 level single-phase half bridge MMC</th>
<th>RL load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor filters</td>
<td>Arm inductors</td>
</tr>
<tr>
<td>Group card board</td>
<td></td>
</tr>
</tbody>
</table>

2nd Joint Experiments within IRPWind

• This second project will build on the results of that project and it will focus on the real world application of the HD-MMC. The project will be split into two stages:
  • The first stage will evaluate the impact of the HD-MMC on the performance of a 3 phase converter with high level control integration.
  • The second stage will look at the real world application of the HD-MMC converter under two scenarios. One connected to an offshore wind turbine generator and the other one connected to an AC inter-array grid.

• SINTEF is the host institution, and ORE Catapult and Tecnalia are users. The control algorithm for a HD-MMC was developed at ORE Catapult in a simulation environment. MMC implementation was made by SINTEF. ORE Catapult, Tecnalia and SINTEF performed the experiments in November. Tecnalia/IREC acts as an impartial referee during the comparison of both techniques C-MMC vs HD-MMC since it has no conflict of interest in the project.

Access to SINTEF lab

SINTEF Energy Research has three different MMCs:
• MMC unit with half bridge cells with 18 cells per arm
• MMC unit with full bridge cells with 12 cells per arm
• MMC unit with half bridge cells with 6 cells per arm
HD-MMC on the performance in 3 phase converter

Objectives
- Ensure proper operation of the HD-MMC in 3 phases with a high level power control
- Correct voltage levels created
- Module voltages are stable and correct
- Compare efficiency/THD trade off compared to C-MMC using PWM and NLM

Set-Up
- GES creates constant, stable AC grid
- GES creates constant, stable DC bus
- MMC operates in PQ mode.

HD-MMC on the performance in 3 phase converter

18 cases were performed.
- It includes C-MMC with NLM and PWM (as a reference case)
- Different combination with HD-MMC
- The weight value is a mechanism that helps the sorting process by giving priority to capacitor voltage balancing or efficiency.

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>Converter</th>
<th>Configuration</th>
<th>Weighting Factor</th>
<th>Modulation Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>C-MMC</td>
<td>[18 00]</td>
<td>0</td>
<td>NLM</td>
</tr>
<tr>
<td>101</td>
<td>C-MMC</td>
<td>[18 00]</td>
<td>500</td>
<td>NLM</td>
</tr>
<tr>
<td>102</td>
<td>C-MMC</td>
<td>[18 00]</td>
<td>500</td>
<td>PWM</td>
</tr>
<tr>
<td>103</td>
<td>C-MMC</td>
<td>[18 00]</td>
<td>500</td>
<td>PWM</td>
</tr>
<tr>
<td>104</td>
<td>HD-MMC</td>
<td>[09 09]</td>
<td>0</td>
<td>NLM</td>
</tr>
<tr>
<td>105</td>
<td>HD-MMC</td>
<td>[09 09]</td>
<td>500</td>
<td>NLM</td>
</tr>
<tr>
<td>106</td>
<td>HD-MMC</td>
<td>[12 06]</td>
<td>0</td>
<td>NLM</td>
</tr>
<tr>
<td>107</td>
<td>HD-MMC</td>
<td>[12 06]</td>
<td>500</td>
<td>NLM</td>
</tr>
<tr>
<td>108</td>
<td>HD-MMC</td>
<td>[15 03]</td>
<td>0</td>
<td>NLM</td>
</tr>
<tr>
<td>109</td>
<td>HD-MMC</td>
<td>[15 03]</td>
<td>500</td>
<td>NLM</td>
</tr>
</tbody>
</table>

HD-MMC on the performance of a 3 phase converter with high level control integration

Objectives
- Determine stability of HD-MMC to sudden control point changes
- Determine the impact the HD-MMC has on the time taken to reach new operating point
- Ensure module voltages remain stable after each step change

Set-Up
- GES creates constant, stable AC grid
- GES creates constant, stable DC bus
- MMC operates in PQ mode. PQ references are used to create step changes in Apparent Power (S) magnitude or angle.
Conclusions

This work was part of the 2nd call for Joint Experiments organized within The Research Infrastructure WP of IRPWind.

The main goals were achieved:

(i) The performance of a 3 phase converter with HD-MMC with high level control integration was demonstrated. The performance of the HD-MMC to a C-MMC using THD and efficiency was verified. While the primary goal of HD-MMC, which is to reduce the THD was achieved.

(ii) The control stability and system response was verified through stepping the control set points and rapid changes in grid voltage and frequency to emulate potential grid variation and disturbances

(iii) The HD-MMC concept was tested in more real world conditions such as the connection of an emulated generated with real data.
1. Context and Problem Statement

• Usual to utilize offshore turbines designed for a fixed base on floating platforms
• FOWT experience increased tower base for-aft moments due to platform motion

All pitch-to-feather HAWTs experience ‘negative damping’ which can cause tower fore-aft oscillations that increase the loads on the tower

Advanced control strategies can reduce the platform motion and hence loads on the tower
1. Context and Problem Statement

- Advanced control strategies can reduce the platform motion and hence loads on the tower.
- Blades that pitch-to-stall cause a drag force which increases with wind speed, therefore avoid undesirable ‘negative damping’ effects.

2. Aim, Objectives & Approach

The aim is to assess whether pitching the turbine blades actively to stall in Region III, using advanced control strategies, could aid in reducing the loads on the tower of a turbine coupled to a semi-submersible platform design.

- DeepCwind semisubmersible model coupled to the three bladed NREL 5MW HAWT.
- Controllers designed in Simulink (MATLAB)
- Simulations utilizing FAST to predict system responses and loads in the time domain.

- Controllers designed in Simulink (MATLAB)
- Simulations utilizing FAST to predict system responses and loads in the time domain.
- Fast provides an inbuilt interface with Simulink.

- DeepCwind semisubmersible model coupled to the three bladed NREL 5MW HAWT.
2. Aim, Objectives & Approach

- DeepCwind semisubmersible model coupled to the three bladed NREL 5MW HAWT.
- Controllers designed in Simulink (MATLAB)
- Simulations utilizing FAST to predict system responses and loads in the time domain.
- Fast provides an inbuilt interface with Simulink.
- Identify fatigue reduction benefits available from different control strategies.

3. Results - Baseline pitch-to-stall controller

- Constant gain, closed-loop, feedback PI pitch controller
- Input = Error (the difference between the set-point (rated) and the actual rotor speed)
- Output = the summed results after $K_P$ & $K_I$ are applied & added to the equilibrium pitch value

3. Results - Periodic steady wind responses

- Initially unstable and would not converge
- $K_P$ & $K_I$ gains increased
- Excessive blade deflections - striking the tower
- Blade flapwise stiffness increased
- A realistic active stall designed blade would be preferable

3. Results - Periodic steady wind responses

- Reduction in blade pitch angle in stall (-8.1° compared to 22.9°)

3. Results - Periodic steady wind responses

- Initially unstable and would not converge
- $K_P$ & $K_I$ gains increased
- Positive thrust force i.e. avoiding the negative damping (891kN to 1361kN stall) (891kN to 402kN feather)
3. Results - Periodic steady wind responses

- Reduction in blade pitch angle in stall (-4.1° compared to 22.9°)
- Positive thrust force (i.e., avoiding the negative damping) (89kN to 1361kN stall) (89kN to 402kN feather)
- Performance equal

3. Results - Gain scheduling benefits

- 12mps mean turbulent winds irregular waves Hs 2m, Tp 7s
- Gain scheduling more complex in stall, may require 2 controller schedules
  - Faster response
  - Improved performance

3. Results - Tower base fore-aft load mitigation

- 18mps mean turbulent winds irregular waves Hs 4m, Tp 10s
- Response too slow with calculated gains
  - Proportional gain too low
### 3. Results - Tower base fore-aft load mitigation

- 18mps mean turbulent winds irregular waves $H_s$ 4m, $T_p$ 10s
- Response too slow with calculated gains proportional gain too low
- Pitch actuation increased

### 4. Conclusions

- A robust control system with gain scheduling for stall operation could be further enhanced when coupled to other advanced control strategies.
- Increasing the gains gave improved performance and reductions in the tower base fore-aft moment range

---

### 3. Results - Tower base fore-aft load mitigation

- 18mps mean turbulent winds irregular waves $H_s$ 4m, $T_p$ 10s
- Response too slow with calculated gains proportional gain too low
- Pitch actuation increased
- Performance improved

### 4. Conclusions

- A robust control system with gain scheduling for stall operation could be further enhanced when coupled to other advanced control strategies.
- Increasing the gains gave improved performance and reductions in the tower base fore-aft moment range

---

### 3. Results - Tower base fore-aft load mitigation

- 18mps mean turbulent winds irregular waves $H_s$ 4m, $T_p$ 10s
- Response too slow with calculated gains proportional gain too low
- Pitch actuation increased
- Performance improved
- Tower base fore-aft moment range & StD lower than F2

### 4. Conclusions

- A robust control system with gain scheduling for stall operation could be further enhanced when coupled to other advanced control strategies.
- Increasing the gains gave improved performance and reductions in the tower base fore-aft moment range
- The increase in positive mean of the platform pitch and tower fore-aft motions compared to feather indicate that this platform’s stability would need increasing, for a pitch to stall operating regime.
Thank you for your time

Questions and Advice welcome

Dawn.Ward@cranfield.ac.uk
A2) New turbine and generator technology

Integrated design of a semi-submersible floating vertical axis wind turbine (VAWT) with active blade pitch control, F.Huijs, GustoMSC

Evaluation of control methods for floating offshore wind turbines, W.Yu, University of Stuttgart

Impact of the aerodynamic model on the modelling of the behaviour of a Floating Vertical Axis Wind Turbine, V.Leroy, LHEEA and INNOSEA
INTRODUCTION – FLOATING VAWT

• Deeper waters
• Larger wind turbines
• Increasing interest for floating wind
• Low centre of gravity position
• Large allowable tilt angle
• Potential for scaling up
• VAWT promising for floating

INTRODUCTION – PREVIOUS WORK

Technip, Nenuphar
Cahoy et al, OTC 21704, 2011

DeepWind project
Pauten et al, DeepWind2013

GustoMSC, TU Delft
Blonk, MSc thesis, 2010

INTRODUCTION – S4VAWT PROJECT

• Active blade pitch control for VAWT
• Improved aerodynamic efficiency (power production)
• Lower wind loads above rated (power production)
• Lower survival loads (parked)

• Objectives S4VAWT project:
  • Verify & quantify VAWT advantages
  • Design semi-submersible floater
  • Verify design by simulations

OUTLINE

• Introduction
• Floating VAWT design
• Coupled analysis
• Conclusions
**DESIGN – BASIS**

- 6 MW VAWT
- Maximum static tilt during production < 10°
- French Mediterranean Sea
- Water depth ~ 100 m
- 50-year significant wave height ~ 6.5 m
- DNV GL standards

**DESIGN – 6 MW VAWT**

- Active blade pitch control

**COUPLED ANALYSIS – SOFTWARE**

- Aerodynamics: Lifting line free vortex wake method
- Turbine and control: Structural dynamics, gyroscopic effects, etc.
- Hydrodynamics: Potential flow, full QTF, quadratic damping
- Mooring: Dynamic lumped-mass model

**COUPLED ANALYSIS – MOTION RESULTS**

<table>
<thead>
<tr>
<th></th>
<th>Rated</th>
<th>Cut-out</th>
<th>Survival</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-min mean wind velocity [m/s]</td>
<td>11</td>
<td>25</td>
<td>39</td>
</tr>
<tr>
<td>Significant wave height [m]</td>
<td>4.0</td>
<td>5.4</td>
<td>6.5</td>
</tr>
<tr>
<td>Floater surge [m]</td>
<td>mean</td>
<td>42</td>
<td>42</td>
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<tr>
<td></td>
<td>max</td>
<td>46</td>
<td>51</td>
</tr>
<tr>
<td>Floater tilt (roll &amp; pitch) [deg]</td>
<td>mean</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>Floater yaw [deg]</td>
<td>mean</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>
**CONCLUSIONS – FLOATING VAWT DESIGN**

- Active blade pitch control makes design drivers floater for VAWT more similar to HAWT:
  - Rated wind governing for floater tilt & tower base moment
  - Parked survival still governing for surge & mooring tensions

- Yaw induced by rotor torque no issue for Tri-Floater

**CONCLUSIONS – VAWT**

- Known advantages VAWT for floating wind:
  - Low centre of gravity position
  - Large allowable tilt angle
  - Potential for scaling up

- Active blade pitch control:
  - Mitigate large loads above rated and parked

- Floater for VAWT 20% lighter than for HAWT
Evaluation of control methods for floating offshore wind turbines

**What makes controlling FOWTs difficult?**

Physical: Negative aerodynamic damping

Applying conventional on-shore controller to FOWT leads to the instability problem.


**Background & Motivation**

EU Horizon 2020 project: TELWIND

Cost reduction for floating offshore turbine

- Evolved spar concept
- Telescopic tower
- Local and low cost material usage: Concrete
- Simpler manufacturing and installation processes

**How good do the state-of-art controllers work?**

Selection of theoretical methods

Different control methods used for FOWT by modifying Baseline controller:

- Single-input-single-output (SISO): Detuning / scheduled detuning
- Multi-input-single-output (MISO): Ptfm damper - feedback of Ptfm-Pitch to blade-Pitch
- Multi-input-single-output (MIMO): Compensator - feedback of Ptfm-Pitch to generator torque

Evaluation tool:

- Linear analysis: simplified linear model with 5 DOF (BLOW)
- Coupled aero-hydro-servo-elastic nonlinear model (Bladed v4.7)

**How well do the state-of-art control methods work?**

Simple approach

**SISO: Detuning**

1DOF Drivetrain: second order differential system

Eigen-frequency of the drivetrain motion should be lower than the Ptfm eigen-frequency

Detuning method could lead to negative gains at higher wind speed
**SISO: Detuning**
Scheduling at different wind speeds

- **Baseline controller**
- **High stability**
- **Medien stability**
- **Low stability**

RHPZ problem differs from the operating wind speed, thus detuning should be applied according to the operating point.

**MISO: Feedback of Ptfm-Pitch to Blade-pitch**
Problem with wave

Due to the difficulty on filtering out the signal in wave frequencies, Ptfm Damper doesn’t work well for Ptfms with pitch eigen-frequency close to the wave frequencies.

**SISO: Detuning**
Trade-off between system stability and control performance

- **Baseline controller**
- **High stability**
- **Medien stability**
- **Low stability**

Higher stability is at the cost of the control performance.

**MIMO: Feedback of Ptfm Pitch to Gen Torque**
How does it work?

A RHPZ Compensator can solve the trade-off problem by moving the positive zero to the left s-plane, however will increase the maximum loads on the generator torque.

**MISO: Feedback of Ptfm-Pitch to Blade-pitch**
How does it work?

Ptfm-damper can increase the pitch stability, however the trade-off between stability and control performance still exist.
Conclusion

- System motions and loads are strongly influenced by the controller. These can be significantly reduced by a well designed controller.

- Additional loops can improve the control performance. However, all of the state-of-art approaches have drawbacks.

- Improvement of control performance in wave frequency region is difficult with current sensor and actuators.
Impact of the aerodynamic model on the modelling of the behaviour of a Floating Vertical Axis Wind Turbine

Vincent LEROY¹,²
PhD Student
J.-C. GILLOTEAUX¹, A. COMBOURIEU², A. BABARIT¹, P. FERRANT¹

¹LHEEA – Centrale Nantes – 1, rue de la Noë – 44321 Nantes - FRANCE
²INNOSEA – 1 rue de la Noë – 44321 Nantes - FRANCE

Unsteady aerodynamics of a VAWT at sea

DeepWind VAWT (Paulsen et al., 2014)

Unsteady aerodynamics of a VAWT at sea

Modular coupling

A control module dedicated to floating VAWTs (Merz et al., 2013) and adapted as (Cheng, 2016) for our study, filtering intermediate frequencies.

Which model can we use for a FVAWT?

Amongst other theories...
- Inviscid models can usually account for viscous effects with semi empirical models

<table>
<thead>
<tr>
<th>Model</th>
<th>Assumptions</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMS [1]</td>
<td>Double Multiple Streamtube</td>
<td>Steady Unsteady flow</td>
<td>Actuator disks</td>
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<tr>
<td></td>
<td></td>
<td>Fast State-of-the-art</td>
<td>Steady Problems at high TSRs</td>
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<td>flow</td>
<td>sweep Viscous models added</td>
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<td>Liftig law</td>
<td>2D</td>
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<tr>
<td>QFD [4]</td>
<td>Actuator line + RANS</td>
<td>Unsteady aerodynamics</td>
<td>High CPU cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inherent rotor/wake/wake</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>wake/wake interactions</td>
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</table>

Aerodynamic modelling of VAWTs

OC3 load cases on the H2 + OC3Hywind SPAR

- Environmental conditions
  - $T_w = 10x$, $H_s = 6m$
  - Kaimal spectrum wind ($x, y, t$)
    - $U_{10} = 12m.s^{-1}$ $75R = 3.5$
    - $U_{10} = 18m.s^{-1}$ $75R = 2$

- Simulations run on 5 000s
  - Transient regime removed for analysis

- Relevant output data
  - Platform motions 6 DOFs
  - Aerodynamic loads and power on the rotor ($F_x, F_y, P$)
  - Aerodynamic loads on an equatoral blade element $F_x, F_y$

NREL 5MW HAWT on the OC3Hywind SPAR (Jonkman, 2010)
2 and 3 bladed H-VAWTs of equal solidity, on the OC3Hywind SPAR
- Designed by (Cheng, 2016)
- Same mooring system, with an added linear spring acting in yaw (Jonkman, 2010)
- Rigid bodies (SPAR, tower and blades)
- Studied:
  - Motion RAOs with “white noise” waves and constant wind (DMS vs. FVW)
  - OC3 load cases, in time domain for the VAWTs with DMS vs. FVW solvers
  - H2 presented today

Studied Floating HAWT and VAWTs

- NREL SMW HAWT on the OC3Hywind SPAR (Jonkman, 2010)
- 2 and 3 bladed H-VAWTs of equal solidity, on the OC3Hywind SPAR
  - Designed by (Cheng, 2016)
- Same mooring system, with an added linear spring acting in yaw (Jonkman, 2010)
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Power Spectral Densities: platform motions

- Lower damping with DMS
- Pitch natural freq.
- Wave freq. response
- Low freq. response (mooring)
- Higher torque with FVW

Power Spectral Densities: aerodynamic loads

- Higher torque with FVW
- 2p freq.

Power Spectral Densities: conclusions

- Similar motion PSDs in response to the two models: DMS and FVW
  - Surge, Heave, Pitch
  - Yaw (at natural frequency)
  - At waves and low frequencies
- Higher damping on the transversal motions with FVW
  - Differences in sway and roll at natural frequencies
- Important differences at high TSRs for the torque PSDs
  - At the 2p frequency
  - Similar behaviour at low frequencies

Mean and std: platform motions

- Relative differences: DMS vs. FVW
  - Mean(X) 12% 6%
  - Std(X) 1% 6%
  - Mean(Y) 9% 11%
  - Std(Y) 14% 3%
- Diff. in heave comes from pitch coupling

Mean and std: aerodynamics

- Relative differences: DMS vs. FVW
  - Mean(Cx) 12% 6%
  - Std(Cx) 15% 9%
  - Mean(Cy) 19% 5%
  - Std(Cy) 11% 8%
Loads on a blade element

- Tangential load on equatorial blade element on a revolution
  - 25% relative difference on mean load at 12m s⁻¹
  - 37% relative difference on std at 12m s⁻¹
- Impact if considering flexible blades?

Impact of the aerodynamic model on the H2 (OC3 load case):
- DMS vs. FVW
  - No substantial effect on PSDs (except transversal motions)
  - Same conclusion on the motion RAOs with wind

When focusing on mean and std:
- At low TSR: Models behave similarly
- At high TSR: Important differences on mean and std for:
  - Aerodynamic loads
  - Motions

⇒ DMS seems to miss important aerodynamic unsteady effects due to strong rotor/wake interactions at high TSR
⇒ It could have a strong impact when looking at blade design (with flexible blades), for instance

Similar conclusions are obtained with the H3 (VAWT) on the same load cases (not presented here...)
⇒ Comparative study to come

References


H. A. Madsen, “The actuator cylinder - A flow model for vertical axis wind turbines”, Aalborg University Centre, Denmark, 1982


Z. Cheng, “Integrated Dynamic Analysis of Floating Vertical Axis Wind Turbine”, Norwegian University of Science and Technology (NTNU), 2016

Key features:
- Hydrodynamics: linear potential flow solver Nemoh (developed at Centrale Nantes)
- Mechanics: multi-body solver
- Quasi-steady mooring model (MAP++)
- Accounts for Power Take Off (generator) and control laws (blade pitch and/or generator)
- Solves the equations of motion in time domain using RK4 or Adams-Moulton scheme
- Considers regular or irregular waves

Coupled simulation tool: seakeeping

InWave is developed at INNOSEA in collaboration with LHEEA Lab. of Centrale Nantes

Contact: vincent.leroy@ec-nantes.fr
### Coupled simulation tool: FVW solver

- **CACTUS**
  - Code for Axial and Cross-flow Turbine Simulation
  - Developed at Sandia National Laboratories (BSD License)

- **Free Vortex Wake theory – lifting line theory**
  - Potential flow, unsteady
  - Either HAWT or VAWT
  - Works with known profiles ($C_u, C_p, C_m$)
  - Inherently accounts for tip vortices, rotor/wake interactions, skewed inflow

- **Computes**
  - Unsteady aerodynamic loads, including the tower shadow

- **Validated**
  - on fixed horizontal and vertical rotors

- **Added**
  - Parallel computing, turbulent inflow, visualizations, platform motions

### Coupled simulation tool: DMS solver

- **Theory from Paraschivoiu (2002)**
  - Assumes steady and potential flow
  - Large number of double streamtubes
  - With actuator disks upwind and downwind

- **Added**
  - Leishman-Beddoes dynamic stall model
  - Skew model as presented in Wang (2003)
  - Validated on a fixed turbine (SANDIA 17m) (Akins, 1986)
  - And in a skewed flow (Mertens, 2003)

### Control algorithm (Merz, 2013)

- Adapted by (Cheng, 2016)

### Motion RAOs from time domain

- **Conditions**
  - White noise waves
  - Constant wind: $U_{ref} = 6, 8, 12, 18$ m s$^{-1}$ (Only BEM (FAS code) for HAWT or DMS for VAWTs)

- **Post-processing**
  - PSD computation as in (Ramachandran et al., 2013)
  - $R\&O(u) = \frac{\text{RAO}(u)}{\text{PSD}(u)}$ on the waves frequencies

- **Coupling with pitch**

### « Code-to-code » comparison

- First study on a floating HAWT with InWave + CACTUS
  - OC3Hywind + NREL5MW (OC3)

- Presented at OMAE2017 @Trondheim, Norway

- Studied Floating HAWT and VAWTs
  - NREL SMW HAWT on the OC3Hywind SPAR (Jonkman, 2010)
  - 2 and 3 bladed H-VAWTs of equal solidity, on the OC3Hywind SPAR
    - Designed by (Cheng, 2016)
  - Same mooring system, with an added linear spring acting in yaw (Jonkman, 2010)
  - Rigid bodies (SPAR, tower and blades)
  - Studied:
    - Motions RAOs from “white noise” waves and wind (DMS vs. FVW)
    - OC3 load cases in time domain for the VAWTs with DMS vs. FVW solvers
    - HD presented today
Impact of aero model and RAOs

- Comparison of these RAOs for VAWTs: DMS vs. FVW

- No effect on heave

- Damping seems to be more important in FVW model

- No other effect on RAOs
B1) Grid connection and power system integration

Ancillary services from wind farms, Prof W. Leithead, Strathclyde University

North Seas Offshore Network: Challenges and its way forward, P. Härtel, Fraunhofer IWES

Towards a fully integrated North Sea Offshore Grid: An engineering-economic assessment of a Power Link Island, M. Korpås, NTNU

Context

To provide full range of Ancillary Services requires:

- Flexible operation of array
- Flexible operation of turbines
- Delivery by wind farm control
- Robustness to comms delays
- Array to act as virtual plant

Worst case scenario:

- GW size array
- Far offshore
- HVDC connection-to-shore

Wind Farm Control Structure

Ancillary Services are delivered by the controller:

- Architecture provides full flexibility of operation
- It is distributed, hierarchical and scalable
**Controller for dispatching changes in power**
- Determines change in output, $\Delta P_i$, required from each turbine

**Wind Farm Control Structure**
- $5\text{MW}$ wind turbine in $9\text{m/s}$ mean wind speed
- Output adjusted in increments of $100\text{kW}$

**Power Adjusting Controller, PAC**
- Adjusts output of turbine $i$ by $\Delta P_i$, as requested
- PAC passes back info on turbine state using flags, $S_i$

**Wind Farm Simulation**
- Provision of synthetic inertia by PAC on $5\text{MW}$ wind turbine
- $7$, $10$ and $20\text{m/s}$ mean wind speed

---

**Wind Farm Control Structure**

**Wind Farm Control Structure**

**Power Adjusting Controller, PAC**
- Adjusts output of turbine $i$ by $\Delta P_i$, as requested
- PAC passes back info on turbine state using flags, $S_i$

**Wind Farm Simulation**

**Wind Farm Simulation**

---

**Wind Farm Control Structure**

**Wind Farm Control Structure**

**Power Adjusting Controller, PAC**
- Adjusts output of turbine $i$ by $\Delta P_i$, as requested
- PAC passes back info on turbine state using flags, $S_i$
Wind Farm Simulation

- **StrathFarm**

![Wind Farm Simulation Diagram]

Current simulation times (for 600s Simulation):
- 5WTs ~ 33s
- 20 WTs ~ 155s

Farm Output Curtailment

- Controller for AS provision acts on \( P_o - P_I \)
- It has integral action
- \( \Delta P \) is continuously updated to drive \( P_o - P_I \) to zero

![Controller for AS provision and dispatching changes in power diagram]

- Wind farm of 10x5MW turbines with mean wind speed of 10m/s.
- Farm output with and without curtailment

![Graphs showing farm output with and without curtailment]
Farm Output Curtailment

- Wind farm output when turbines are curtailed individually.

- Perturbations of power output about target of 25MW increases with time delay.
- Perturbations decrease as number of turbines in farm increases.
- Robustness to communication delays of 2, 4, and 6 seconds.

Farm Level Frequency Support

- Controller for AS provision does not act on $P_f$
- $\Delta P$ is continuously updated in response to grid frequency
- Provides both synthetic inertia and droop control

---

Farm Output Curtailment

- Reduction in wind farm output

Farm Level Frequency Support

- Provision of ancillary services at farm level

- 10x5MW turbines in 2 columns of 5
- Mean wind speed ~ 8m/s
- Turbulence ~10%
- Requested reserve ~ 2MW
Farm Level Frequency Support

- Wind farm provision of frequency support with/without 2MW curtailment

Farm Level Frequency Support

- Change in power for each turbine (with 2MW curtailment)
- Cross-compensation between turbines (needed as wind speed low)

Farm Level Frequency Support

- Operation of each turbine

Virtual Conventional Plant

- Primary response provided by virtual plant

Virtual Conventional Plant

- No frequency support
Virtual Conventional Plant

- Virtual plant with communication delay of 150ms
- GRF with communication delay of 150ms
- Feedforward control applied to HVDC sub-station
- Stability of grid is not compromised

Virtual Conventional Plant

- No frequency support from array
- Shorter delay reduces voltage drop
- Generator-response following control (GRP)

Virtual Conventional Plant

- DC voltage drop due to energy extraction
- GRF with communications delay of 150ms
- Feedforward control applied to HVDC sub-station
- Stability of grid is not compromised

Virtual Conventional Plant

- Virtual plant with communication delay of 150ms
- ~50MW frequency support from array

Virtual Conventional Plant

- 30MW generator
- No frequency support from array

Virtual Conventional Plant

- Generator-response following control (GRP)
- No direct power frequency measurements to reduce delays
- Provides a full range of Ancillary Services, inertia, governor-droop control, reserve, curtailment etc.
- Grid Code Compliant

Conclusion
Conclusion

Provision of full range of Ancillary Services possible at wind farm level

Thank You
Northern Seas Offshore Network (NSON)
Challenges and its way forward

Philipp Härtel, Denis Mende, Kurt Rohrig, Energy Economics and Grid Operation, Fraunhofer IEE
Philipp Hahn, Andreas Bley, Institute of Mathematics, University of Kassel

15th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2018
Trondheim, January 18, 2018

Agenda

I Northern Seas Offshore Network (NSON)
II Modelling stages of the national NSON project in Germany (NSON-DE)
III Challenges for future research
IV Summary

University of Kassel, IETH of Leibniz University Hannover and Fraunhofer IEE are the partners of the national project in Germany (NSON-DE)

NSON-DE has four modelling stages to investigate potential NSON configurations and their impacts on both the German and European energy supply system with consistent data sets and feedback loops.

Modelling stages

1 Market-based grid planning
2 Technology-based grid planning
3 Offshore grid validation
4 Detailed grid representations

Geographical focus

European energy market areas + offshore grid region

NSON-DE is currently being finalised - report to be published by June this year.
The market-based grid planning determines and assesses market-driven investment decisions in a potential NSON, adequately accounting for the directly and indirectly connected onshore market areas.

<table>
<thead>
<tr>
<th>Modelling stage</th>
<th>Geographical focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology-based grid planning</td>
<td>Onshore wind farms</td>
</tr>
<tr>
<td>Offshore grid validation</td>
<td>Offshore grid region</td>
</tr>
<tr>
<td>Onshore grid repercussions</td>
<td>Onshore grid region</td>
</tr>
</tbody>
</table>

Long-term NSON 2050 scenario features high level of decarbonisation due to coupled operation of energy sectors – capturing interaction and flexibility is essential in offshore grid expansion planning.

The large-scale offshore grid expansion planning model has a particular focus on capturing future energy system flexibility in the onshore market areas.

Consistent spatial and meteorological data is used to adequately capture the offshore grid region – final case studies will investigate three topology paradigms for NSON 2030 and 2050.

The technology-based grid planning stage narrows the focus to the offshore grid region and investigates it with a higher level of detail.
Technology-based grid planning stage simultaneously optimises locations of future wind farms, their connection(s) to shore, and the main technical components.

Offshore region
- Planning of an offshore grid with its spatial and technical configuration
- Co-optimisation of offshore wind farm investments
- Co-optimisation of exchange demands and offshore wind capacity targets

Onshore region
- Planning aspects and technical requirements demand some simplifications when co-optimising grid planning and wind farm locations
- Offshore region
  - Various line types (AC, DC, voltage levels, etc.)
  - Technical equipment (converters, transformers, switches)
- Technical requirements
  - Platforms for the equipment
  - Necessary simplifications
    - Temporal resolution (consider subset of weather year)
    - Neglecting physical laws of power flow

Planning aspects and technical requirements demand some simplifications when co-optimising grid planning and wind farm locations.

A test grid instance was used to test the mixed-integer linear program and newly developed heuristics to quickly compute feasible initial solutions.

Due to a large number of time steps and scenarios, an automated approach was developed to electrically validate the market- and technology-based grid planning results.

Onshore grid repercussions induced by different offshore grid topologies are assessed for the onshore transmission system of the German market area.
Market simulation data and offshore grid planning data for the NSON 2030 scenario are combined with a detailed model representing the German part of the continental European transmission system.

### Agenda

- **Northern Seas Offshore Network (NSON)**
- Modelling stages of the national NSON project in Germany (NSON-DE)
- Challenges for future research

### Summary

Northern Seas Offshore Network (NSON) particularly in light of high cross-sectoral decarbonisation targets.

The national NSON project in Germany (NSON-DE) developed a closely linked modelling chain involving several stages, from the economic distribution of offshore systems associated with investment costs and benefits, to market integration, cost-benefit sharing as well as robust grid planning and operation methods.

Over the course of the NSON-DE project a number of remaining challenges were identified for further research:

#### Flexibility and uncertainty in future energy systems

- offshore wind generation, offshore grid planning, offshore grid operation
- market integration, cost-benefit sharing method

#### Grid sharing

- Market integration and cost-benefit sharing
- Energy-from waste
- Market integration and cost-benefit sharing
- Energy-from waste

#### Power System Planning

- Network expansion and offshore grid planning
- Market integration and cost-benefit sharing

#### Conclusions

With a growing amount of offshore wind generation being deployed in Northern Europe, the relevance of a Northern Seas Offshore Network (NSON) increases dramatically. A comprehensive model of the European electricity system is a prerequisite for a highly reliable, energy-efficient and cost-effective offshore grid planning and operation.

The national NSON project in Germany (NSON-DE) develops a closely linked modelling chain involving several stages, from the economic distribution of offshore systems associated with investment costs and benefits, to market integration, cost-benefit sharing as well as robust grid planning and operation methods.

### Thank you very much for your attention!
Towards a fully integrated North Sea Offshore Grid
- An economic analysis of a Power Link Island / OWP hub

Martin Kristiansen
Magnus Korpås
Hossein Farahmand

Keywords: North Sea Offshore Grid, Grid Typologies, Market Integration, Optimization, TEP, GEP

Outline for the talk

1. Main drivers for multinational TEP
   - More renewables → need for flexibility

2. Motivation: Different grid topologies
   - Radial // Meshed // Artificial Island (!)

3. Added value of an artificial island
   - "Power Link Island" versus radial solutions

4. Conclusions and work in progress

More RES yields a demand for infrastructure and flexibility

As we know: More renewables comes into the system

Quarterly Investments by Assets (ex. R&D)

...causes a more volatile net-load

Power Link Island
Artificial island for transnational power exchange and distribution of offshore wind resources
Each PLI can include 30 GW offshore wind

**Power Link Island**
- **Capacity:** 30 GW offshore wind
- **6 km² (0.02% Dogger Bank)**
- **Supply 23-30 million people**

**Financing:**
- €1.5bn for rocks & sand
- Operational by 2035
- **Economies of scale**

**Technical:**
- Offshore wind hub
- Transnational exchange hub
- Power-to-gas potential

Reference [TenneT, 2017] with modifications

---

**Power Link VS radial**
Assessing their performance with an optimization model for both investments and operation.

North Sea Offshore Grid 2030 Case study (ENTSO-E Vision 4)

---

...with expected cost savings due to economies of scale

**Base case including OWP grid integration costs**

- **Grid**
  - 2030 planned infrastructure
  - Domestic grid restrictions (~5 to 15 GW)
- **Supply and demand**
  - ENTSO-E Vision 4 (“Green Revolution”)
  - 65 GW OWP (Peak demand is 150 GW)
- **Power flow modelling**
  - Transport model due to HVDC connections
- **Representation of hourly variability**
  - Time series based on given geo coordinates
  - Hydroelectric represented with hourly price series (water value)
  - Seasonal characteristics
- **Hourly load**
  - ENTSO-E
- **Goal**
  - Include OWP to the lowest possible costs
  - 1. Radial solutions
  - 2. Power Link Island

---

**Value of having the possibility to invest in PLI**

- **Radial base case**
  - PLI as a hub
  - No OWP capacity at the PLI

Total operation costs of the system (30 yrs)
- **Radial:** € 629 B
- **PLI:** € 610 B
- **Cost savings:** € 19
Value of connecting offshore wind to the island

What is the cost savings from adding OWP to PLI including the option to expand interconnectors even more than planned capacities?

Including generation expansion

Assuming planned interconnectors for 2030. What are the cost savings allowing for PLI when trying to anticipate changes in the generation mix? ENSTO-E V4 exogenous plus additional Generation Expansion Planning (GEP).

PLI without offshore wind allocated to it

• Radial expansion base case
  • No OWP at PLI
  • Allow interconnector expansion

Total operation cost of the system over 30 years
• €597 B

PLI with GEP base case as reference

• Radial base
  • OWP already integrated for free
  • GEP (except for hydro or nuclear)
  • TEP for a PLI
• No additional interconnectors

Total operation costs of the system:
• € 507 B
• € 496 B
• Cost savings €11 B

• ... significant cost savings also when accounting for GEP (i.e. a stable GTEP equilibrium before PLI TEP)

PLI with 30 GW allocated to it

• Compared to radial exp base case
  • Allow interconnector expansion
  • 30 GW at PLI (Realocating from GB)

Total operation costs of the system
• Without PLI: €597 B
• With PLI: €589 B
• Cost savings = €8 B

Meshed solutions

Some meshed alternatives to include offshore wind power
Base case incl costs for connecting OWP (meshed)

- Meshed base case (without interconnector expansion)
  - Radial: €629 B
  - Radial + PLI: €610 B
  - Meshed: €611 B

...it has an even more clear impact on CO2 emissions

Base incl costs for including OWP (meshed) + PLI (as hub)

- Meshed base case
  - PLI as a hub (no wind allocated)
  - No additional interconnectors
  - Radial: €629 B
  - Radial + PLI: €610 B
  - Meshed: €611 B
  - Meshed + PLI: €609 B
  - Cost savings: €2 B

“PLI yields significant costs savings for an integrated NSOG”

Key takeaway so far:

- The PLI provides a more cost-efficient OWP integration than radial solutions, reducing curtailment of wind as well as increasing trade possibilities (spatial flexibility) at a lower investment cost.
- It is shown that the relative value of a PLI increases when the level of offshore wind power capacity increases.

Limitations and future work:

- Cost uncertainty
- Unit commitment
- Multi-sector
- Onshore grid representation
- Local flexibility

PLI shows increasing value when OWP capacity increases

Relevant findings from the optimization model:

- Different comparisons of radial- and PLI integration of OWP capacity yield system cost savings up to €19 B over 30 years depending on the degrees of freedom in the planning model.
- When trying to anticipate the impact of generator expansion, the added value from the PLI is still significant (~€11 B).
- Assuming other flexible grid integration alternatives, such as a meshed grid, the added value of a PLI is expected to be around €2B.

Assuming other flexible grid integration alternatives, such as a meshed grid, the added value of a PLI is expected to be around €2B.
Contents

- Introduction
- Voltage Stability
- Frequency Stability
- Conclusion

Introduction

Grid Codes Summaries

- Are valid today – possibly not in the future
- Are valid for a specific TSO are – not generally valid
- Are readable for lawyers – not necessarily for engineers
- Contain many pages – not giving a easy overview

Real Grid Codes

- Are valid today – possibly not in the future
- Are valid for a specific TSO are – not generally valid
- Are readable for lawyers – not necessarily for engineers
- Contain many pages – not giving a easy overview

ENTSO-E Grid Codes

- Are valid today – possibly not in the future
- Are valid for a specific TSO are – not generally valid
- Are readable for lawyers – not necessarily for engineers
- Contain many pages – not giving a easy overview
Introduction

ENTSO-E Grid Codes

- Are valid today – possibly not in the future
- Are valid for a specific TSO are – not generally valid
- Are readable for lawyers – not necessarily for engineers
- Contain many pages – not giving an easy overview

Introduction

What does Academia need?

- Are valid today – possibly not in the future
- Are valid for a specific TSO are – not generally valid
- Are readable for lawyers – not necessarily for engineers
- Contain many pages – not giving an easy overview
- Don’t specify all the details – (…specified by the relevant TSO…)

Introduction

Approach

• Develop a new generic grid code for Academic research purposes regarding wind power in Europe
• Future oriented
• Generic and general
• Readable for engineers
• Few pages-no §s
• Specify the relevant details

An activity within IRPWind project

Introduction

Goal

• A most restrictive grid code as seen from turbine perspective
• "worst case" for wind industry
• Challenging to comply to
• Not a proposal as WindEurope would come up with...
• Good for checking capabilities of new technology concepts
• "if you can comply this, you likely can comply real codes too"
Contents

- Introduction
- Voltage Stability
- Frequency Stability
- Conclusion

Voltage Stability

Fault Ride Through

*Fig. 3: Fault ride through requirement and test fault*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{i0} )</td>
<td>±0.15</td>
<td>pu</td>
</tr>
<tr>
<td>( K_{f} )</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>( I_{i0} )</td>
<td>1.12</td>
<td>pu</td>
</tr>
<tr>
<td>( P_{r} ) (( L_{p} = 1 ))</td>
<td>0.50</td>
<td>pu</td>
</tr>
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</table>

Support Tolerance Band

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta V )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta V_{	ext{max}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta V_{	ext{min}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_{	ext{tol}} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compliance – Reactive Current

*Fig. 3: Reactive current response compliance*
Contents

- Introduction
- Voltage Stability
- Frequency Stability
- Conclusion

**Voltage Stability Compliance – Active Current**

![Graph showing Voltage Stability Compliance – Active Current](image)

**Frequency Stability Frequency Support**

![Diagram showing Frequency Stability Frequency Support](image)

**Frequency Stability Disturbance Ride Through**

![Graph showing Frequency Stability Disturbance Ride Through](image)

**Frequency Stability Compliance**

![Graph showing Frequency Stability Compliance](image)
Conclusion

Summary

• Development of a strict but user-friendly generic grid code
• Helpful for academic studies regarding general future-oriented compliance
• Continuous definition of requirements
  • Determining the exact moment of a fault/disturbance event not necessary

Conclusion

Outlook

• Overvoltage/Overfrequency
• Specification on voltage measurement
Conclusion
Outlook

• Overvoltage/Overfrequency
• Specification on voltage measurement
  • Asymmetric faults

Simultaneous overvoltage and undervoltage on different phases?
B2) Grid connection and power system integration

Statistical Analysis of Offshore Wind and other VRE Generation to Estimate the Variability in Future Residual Load, M. Koivisto, DTU Wind Energy

A demonstrator for experimental testing integration of offshore wind farms with HVDC connection, S. D’Arco, SINTEF Energi

Optimal Operation of Large Scale Flexible Hydrogen Production in Constrained Transmission Grids with Stochastic Wind Power, E. F. Bødal, NTNU

Small signal modelling and eigenvalue analysis of multiterminal HVDC grids, Salvatore D’Arco, SINTEF Energi AS
Statistical Analysis of Offshore Wind and other VRE Generation to Estimate the Variability in Future Residual Load

Matti Koivisto
DTU Wind Energy

January 18th 2018
EERA DeepWind’18
Grid connection and power system integration
Trondheim, Norway

Outline of the presentation

1. The analyzed base scenarios
2. The time series data used
3. Correlations between load and VRE generation
4. A modified 2050 scenario
5. Resulting residual loads in the scenarios
6. Discussion and future work
7. Conclusions

The analyzed base scenarios

- The base scenarios
  - Around 36 GW of VRE generation in 2030 for the analysed countries
  - Around 60 GW in 2050
  - From Nordic Energy Technology Perspectives (NETP) 2016
    - http://www.nordicenergy.org/project/nordic-energy-technology-perspectives/
- These are the base scenarios used in the Flex4RES project
  - http://www.nordicenergy.org/flagship/flex4res/
- The authors would like to acknowledge support from the Flex4RES project and the NSON-DK (ForskEL) project

Simulated VRE generation

- The VRE generation time series are simulated using the CorRES tool developed at DTU Wind Energy
- Based on meteorological data obtained from the mesoscale Weather Research and Forecasting (WRF) model
- Reanalysis of past weather
- Mesoscale models tend to underestimate short-term variability in wind speeds, especially for offshore wind
- To reach more realistic simulations, stochastic fluctuations are added on top of the mesoscale wind speed data
- VRE installation locations
  - When available, existing locations were used
  - For offshore, also planned locations were used
  - For solar PV, installations were assumed to be scattered through the analysed regions

Historical load time series

- Four years of hourly historical load data (2012 to 2015) for the analysed countries were acquired from Nord Pool
  - https://www.nordpoolgroup.com/historical-market-data/
- A few clearly incorrect data points were fixed by using the data from the previous day of the same type (e.g., working day) from the same hour of the day

Correlations in load time series

<table>
<thead>
<tr>
<th>Country</th>
<th>DK</th>
<th>EE</th>
<th>FI</th>
<th>LT</th>
<th>LV</th>
<th>NO</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DK</td>
<td>0.90</td>
<td>0.90</td>
<td>0.76</td>
<td>0.70</td>
<td>0.71</td>
<td>0.93</td>
<td>0.83</td>
</tr>
<tr>
<td>EE</td>
<td>0.90</td>
<td>0.90</td>
<td>0.87</td>
<td>0.85</td>
<td>0.87</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>FI</td>
<td>0.76</td>
<td>0.90</td>
<td>0.70</td>
<td>0.71</td>
<td>0.93</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>LT</td>
<td>0.92</td>
<td>0.97</td>
<td>0.70</td>
<td>0.89</td>
<td>0.62</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>LV</td>
<td>0.87</td>
<td>0.85</td>
<td>0.76</td>
<td>0.89</td>
<td>0.80</td>
<td>0.73</td>
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<tr>
<td>NO</td>
<td>0.73</td>
<td>0.87</td>
<td>0.93</td>
<td>0.62</td>
<td>0.65</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>SE</td>
<td>0.83</td>
<td>0.93</td>
<td>0.95</td>
<td>0.74</td>
<td>0.73</td>
<td>0.96</td>
<td></td>
</tr>
</tbody>
</table>

- Correlations are generally very high
- Countries further away (e.g., DK and FI) have lower correlations
- SD of the aggregate load is 9.01 GW
  - If all load time series would be fully correlated, the SD of the aggregate would be 9.41 GW
  - There is thus only about 4% reduction in RSD due to loads not being fully correlated

Relative standard deviation (RSD) is standard deviation (SD) divided by mean

Aggregate RSD: 0.19
Correlations in load time series ramp rates

- Ramp rates are analysed as first differences of hourly data
- \( \text{diff}(y_t) = y_t - y_{t-1} \)
- Correlations are generally very high
- SD of the aggregate load 1st difference is 1.59 GW/h
- If all load time series would be fully correlated, the SD of the aggregate 1st difference would be 1.72 GW/h
- There is thus about 8 % reduction in ramp rate SD due to loads not being fully correlated

Correlations between VRE generation sources and aggregate load (2/2)

- Both wind generation types are positively correlated with load
- As expected, solar PV is negatively correlated with load
- Solar generation is negatively correlated with wind generation
  - Can reduce residual load variability
  \[ \text{Var}(y_t + x_t) = \sigma_y^2 + \sigma_x^2 + 2\sigma_y\sigma_x\rho_{yx} \]

Behavior of different VRE generation types

- SDs are on average higher in offshore than onshore wind generation
- However, the higher mean generation causes the RSD to be on average 8 % lower in offshore than in onshore wind generation
- Hourly ramp rate SDs are much higher in offshore than in onshore generation
- Solar PV has higher RSD than either of the wind generation types
A modified 2050 scenario

- Modifications were tested for the base 2050 scenario.
  - Expected yearly VRE energy generation was kept constant in all test scenarios.
  - Increasing the low offshore wind share in the baseline scenario up to 50% resulted in a small reduction of the residual load SD (up to 2%).
  - Increasing the overall geographical distribution of wind decreased the residual load SD about 4%.
  - A final modified 2050 scenario:
    - 30% of wind energy from offshore, and solar share 10%.
    - Installations geographically more dispersed.

Percentages of expected yearly energies coming from the different VRE types in the different scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Offshore wind</th>
<th>Onshore wind</th>
<th>Solar PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030 base scenario</td>
<td>15%</td>
<td>83%</td>
<td>2%</td>
</tr>
<tr>
<td>2050 base scenario</td>
<td>9%</td>
<td>90%</td>
<td>1%</td>
</tr>
<tr>
<td>2050 modified</td>
<td>27%</td>
<td>63%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Expected yearly VRE energy generation was kept constant in all test scenarios.

- Increasing the low offshore wind share in the baseline scenario up to 50% resulted in a small reduction of the residual load SD (up to 2%).
- Increasing the overall geographical distribution of wind decreased the residual load SD about 4%.
- A final modified 2050 scenario:
  - 30% of wind energy from offshore, and solar share 10%.
  - Installations geographically more dispersed.

Resulting residual loads

- SD of the residual load increases only by a few percentages compared to only load in the 2030 base scenario - but notably in 2050 (22% higher than the SD of load only).
- As the mean of residual load decreases at the same time, the RSD increases very significantly.
- The modified 2050 scenario shows about 7% lower SD in residual load than in the base 2050 scenario.

Scenario | Mean (GW) | SD (GW) | 5th percentile (GW) | 95th percentile (GW) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Only load</td>
<td>46.3</td>
<td>9.0</td>
<td>15.0</td>
<td>62.0</td>
</tr>
<tr>
<td>2030 base scenario</td>
<td>36.3</td>
<td>9.2</td>
<td>0.25</td>
<td>52.0</td>
</tr>
<tr>
<td>2050 base scenario</td>
<td>30.1</td>
<td>11.8</td>
<td>0.37</td>
<td>48.8</td>
</tr>
<tr>
<td>2050 modified</td>
<td>30.1</td>
<td>10.2</td>
<td>0.34</td>
<td>48.3</td>
</tr>
</tbody>
</table>

Conclusions

- SD of residual load in the 2050 base scenario expected to be 22% higher than in load only.
- Mean decreases at the same time -> RSD increases significantly.
- There will be thus less energy to be generated by non-VRE generation types, but with higher needs of flexibility.
- In the 2050 base scenario, the residual load ramp rate is expected to be 10% higher than in load only.
- A modified scenario for 2050:
  - 7% lower SD in residual load than in the base 2050 scenario.
  - Residual load ramp rate SD is expected to be even slightly lower than in load only.
- During some high load hours of the year, there is only little VRE generation available in all scenarios.

Future work

- Creating more years of load time series
  - To get different meteorological years into the analysis (e.g., very cold winters).
  - Either by acquiring more historical load data, or by building stochastic time series models of load for the different countries and using past meteorological data to simulate load time series.
- VRE simulations are already available for 35 past meteorological years.
- VRE technology development in the future
  - Changes, e.g., in hub heights and specific power will be implemented to model the capacity factors of future wind generation.
- Optimizing the geographical distribution and VRE generation mix
  - E.g., by minimizing residual load variance.

Resulting residual load ramp rates

- Hourly ramp rates in residual load increase only moderately.
- In the 2050 base scenario, the SD of the residual load ramp rate is 10% higher than in load only.
- The modified scenario shows a much lower ramp rate SD compared to the base 2050 scenario.
- Especially the 95th percentile value is much lower.
- This is explained by the increased solar PV share, as solar up-ramping happens often at the same time as load up-ramping.

Scenario | Ramp rate (GW/h) | 5th percentile (GW/h) | 95th percentile (GW/h) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Only load</td>
<td>1.59</td>
<td>-2.34</td>
<td>3.54</td>
</tr>
<tr>
<td>2030 base scenario</td>
<td>1.62</td>
<td>-2.36</td>
<td>3.52</td>
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<tr>
<td>2050 base scenario</td>
<td>1.75</td>
<td>-2.42</td>
<td>3.64</td>
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<tr>
<td>2050 modified</td>
<td>1.57</td>
<td>-2.38</td>
<td>2.87</td>
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Extra material
### Offshore wind

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Offshore wind</th>
<th>Onshore wind</th>
<th>Solar PV</th>
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<tbody>
<tr>
<td>2030 base scenario</td>
<td>573</td>
<td>1443</td>
<td>250</td>
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<td>573</td>
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<tr>
<td>2050 modified</td>
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<td>1443</td>
<td>250</td>
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### Solar PV

<table>
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<tr>
<th>Scenario</th>
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</thead>
<tbody>
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<td>2030 base scenario</td>
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<td>2050 base scenario</td>
<td>8</td>
</tr>
<tr>
<td>2050 modified</td>
<td>8</td>
</tr>
</tbody>
</table>

### Load TWhs

<table>
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<th>Scenario</th>
<th>Load TWhs</th>
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<tr>
<td>2030 base scenario</td>
<td>87.57</td>
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<tr>
<td>2050 base scenario</td>
<td>141.80</td>
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<tr>
<td>2050 modified</td>
<td>141.78</td>
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</tbody>
</table>

### VRE (all) annual TWhs

<table>
<thead>
<tr>
<th>Year</th>
<th>DK</th>
<th>EE</th>
<th>FI</th>
<th>LT</th>
<th>LV</th>
<th>NO</th>
<th>SE</th>
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<tbody>
<tr>
<td>2014</td>
<td>1271</td>
<td>0</td>
<td>26</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>212</td>
</tr>
</tbody>
</table>

VRE installation in 2014 in total around 13 GW.
A Demonstrator for Experimental Testing
Integration of Offshore Wind Farms With HVDC Connection

S.D’Arco, A. Endegnanew, SINTEF Energi

BEST PATHS PROJECT

Beyond State-of-the-art Technologies for re-Powering AC corridors and multi-Terminal HVDC Systems

- Validate the technical feasibility, impacts and benefits of novel grid technologies,
- Five large-scale demonstrations
  - Deliver solutions that allow for transition from High Voltage Direct Current (HVDC) lines to HVDC grids;
  - Upgrade and repower existing Alternating Current (AC) parts of the network;
  - Integrate superconducting high power DC links within AC meshed network

LARGE SCALE DEMONSTRATIONS

1. HVDC in offshore wind farms and offshore interconnections
2. HVDC-VSC multivendor interoperability
3. Upgrading multiterminal HVDC links
4. Innovative repowering of AC corridors
5. DC Superconducting cable

DEMO 1 Objectives

- To investigate the electrical interactions between HVDC link converters and wind turbine converters in offshore wind farms.
- To de-risk the multivendor and multiterminal schemes: resonances, power flow and control.
- To demonstrate the results in a laboratory environment using scaled models (4-terminal DC grid with MMC VSC prototypes and a Real Time Digital Simulator system to emulate the AC grid).
- To use the validated models to simulate a real grid with offshore wind farms connected in HVDC.
Demonstrator overview

- Three-terminal scheme MMC with
  - MMC with HB cells, 18 cells and 6 cells per arm,
  - MMC with FB cells, 12 cells per arm
- Wind farm emulator
- National smart grid laboratory

Real-time simulation and PHIL capabilities

- OPAL-RT based real time simulator platform
  - 5 parallel cores,
  - 2 FPGAs for IO and small time step simulation,
  - Fiber optic communication
- Egston Composio Grid emulator
  - 200 kVA rated power
  - 6 individual outputs
  - > 10 kHz bandwidth
  - Connected to the OPAL-RT system via fiber optics with 4 µs update rate for measurements and references

Demonstration of HVDC transmission systems connected to offshore wind farms

- Designed and built 3 MMC prototypes
- Tested the converters in point to point and multiterminal configurations
- Planned PHIL experiments with real time model of a wind farm

National Smart Grid Laboratory

- Laboratory formally opened in September 2016 after a major upgrade
- Jointly operated by NTNU and SINTEF
- Reconfigurable layout with multiple ac and dc bus
- Power electronics converters
  - 2 level VSC 60 kVA, MMC 60 kVA
- Electrical machines
  - Synchronous generators, induction machines
- Real-time simulator

MMC Converters

- Three MMC converters were designed from scratch
  - MMC with HB cells, 18 cells per arm
  - MMC with FB cells, 12 cells per arm
  - MMC with HB cells, 6 cells per arm
- Built and successfully tested at full rating
  - 42 modules
  - 144 power cell boards
  - 1764 capacitors
Power cell boards

Assembling stages

Converter performance test

Point-to-point and multiterminal configurations

Wind farm emulator

Interaction of an offshore wind farm with an HVDC

• Complex issues
  • Noise, randomness of event timings, and hardware design
  • Numerical simulations are widely accepted and cost effective
  • Test a wide variety of different cases, however, the fidelity of the results is difficult to assess.
  • Hardware power-in-the-loop (HIL) simulation offers a good balance between test coverage and fidelity.
PHIL experiment: Wind farm connected to VSC-based HVDC

- Simulated wind farm
  - Input: Wind speed and measured voltage
  - Output: Grid emulator reference current
- Hardware
  - Two-level VSC generates a three-phase ac voltage with a fixed frequency
  - The close-loop behaviour of the PHIL setup was stable

Results

Conclusions

- Power hardware-in-the-loop (PHIL) approach combines hardware devices with software simulation.
- The hardware part allows a high fidelity of the results whereas, the software simulation part allows an extensive study of different cases at a reasonable cost.
- Grid integration of wind farm using VSC-based HVDC system was evaluated in PHIL experiment as a proof of concept.
- In the future work, PHIL implementation using modular multilevel concepts will be studied.
Hydrogen Production from Wind and Hydro Power in Constrained Transmission Grids, Considering the stochasticity of wind power

Espen Flo Bødal and Magnus Korpås

Wind Power Stochasticity

• How important is it to include wind power stochasticity in the models?
  – How does it affect costs?
  – How does it affect storage strategies?
  – Does the effect of including hydrogen storage change?

Exploiting energy resources in remote regions

• Many good natural gas and wind resources are located in remote regions
• Lacking transmission capacity and long distances makes development of these resources expensive
• Raggovidda

Regional Power System Model

Electric demand

External Market

Wind Forecasting

• Meteorological forecasts and historic production
• Local quantile regression
• Sampling scenarios, including spatial and temporal correlations
**Rolling Horizon Model**

- Find a plan that works best on average
- Penalize deviations from the plan

**Case Study**

- Finnmark in northern Norway
- Good wind potential and LNG production facility
- Weak transmission connection to the rest of the Nordic power system
- Modelled by a 9 bus system
- Simulated over a period of 10 days

**Model Performance**

- EVPI = 37.6 %
- VSS = 5.6 %

**Hydrogen Storage Strategy**

- Hydrogen storage VS no hydrogen storage
- Slightly higher flow in storage case, increased flow on average by:
  - EV: 0.38 %
  - S120: 0.70 %
  - PI: 1.21 %
- The system already has high flexibility from hydro power
- Hydrogen load could be placed better or distributed to give more effect
- No storage results in rationing of 9.8 MW in all cases

**Power Flow**

- Hydrogen storage VS no hydrogen storage
- Slightly higher flow in storage case, increased flow on average by:
  - EV: 0.38 %
  - S120: 0.70 %
  - PI: 1.21 %
- The system already has high flexibility from hydro power
- Hydrogen load could be placed better or distributed to give more effect
- No storage results in rationing of 9.8 MW in all cases
Conclusion

• A rolling horizon model was developed for assessing the value of including stochastic wind power in a regional power system with hydrogen production
• Case study shows:
  – Reduced costs of 5.6% compared to deterministic solution
  – Potential of reducing costs in stochastic solution up to 37.6%
  – Lower regulation cost and higher import for the better solutions
  – Similar solutions for more than 60 wind samples
  – More flow on the transmission lines when storage is included, better improvement for better uncertainty representation
  – Storage helps to avoid very expensive rationing
Overview of models and methods for stability analysis

- Power system stability is commonly assessed by eigenvalue analysis.
  - Enables analysis and mitigation of oscillatory behaviour or instability due to system configuration, system parameters and controller settings.
- VSCHVDC systems have different dynamics compared to traditional generators.
  - Models of MMCHVDC terminals are currently under development.
- State-space models for HVDC systems can be used for multiple purposes:
  - Analysis, identification and mitigation of oscillations and small-signal instability mechanisms in HVDC transmission schemes.
  - Analysis of controller tuning and interaction between control loops in HVDC terminals.
  - Integration in larger power system models for assessment of how HVDC transmission will influence overall small signal stability and oscillation modes.

Protection and Fault Handling in Offshore HVDC grids

Objectives: Establish tools and guidelines to support the design of multi-terminal offshore HVDC grids aiming to maximise system availability. Focus will be on limiting the effects of failures and the risks associated to unexpected interactions between components.

- Develop models of offshore grid components (cables, transformers, AC and DC breakers, HVDC converters) for electromagnetic transient studies.
- Define guidelines to reduce the risks of unexpected interactions between components during normal and fault conditions.
- Define strategies for protection and fault handling to improve the availability of the grid in case of failures.
- Demonstrate the effectiveness of these tools with numerical simulations (PSDSC, EMTP), real-time simulations (RTDS), Opal-RT and experimental setups.
- Expand the knowledge base on offshore grids by completion of two PhD degrees / PostDoc at NTNU and one in RWTH.

Frequency-Dependent State-Space modelling of HVDC cables

- The modelling approach is based on a lumped circuit and constant parameters.
  - Parallel branches allow for capturing the frequency dependent behavior of the cable.
  - Compatible with a state space representation in the same way as classical models with simple \( R \) sections.
  - Model order depends on the number of parallel branches and the number of \( R \) sections.

Small Signal Modelling and Eigenvalue Analysis of Multiterminal HVDC Grids

Salvatore D’Arco, Jon Are Suul SINTEF Energy AS
State-space frequency-dependent π section modelling

Behavior in a point to point HVDC transmission scheme

Classification of MMC Modelling for eigenvalue analysis

Main conclusions related to cable modelling

Compensated vs. Uncompensated Modulation

- ULM is established for EMT simulations
- Traditional π-section models of HVDC cables are not suitable for dynamic simulation or stability assessment of MMC systems
  - Single inductive branches imply significant under-representation of the damping in the system
- Frequency-dependent (FD) π-model for small-signal stability analysis
  - For a simplified model, representation of cables by equivalent resistance and capacitance can be sufficient
- Developed Matlab code and software tool for generating FD-π models

Compensated Modulation

Uncompensated Modulation

Energy-based modelling is not suitable for this case
Main conclusions related to MMC modelling

- The internal energy storage dynamics of MMCs must be represented for obtaining accurate models
  - Established models of 2-Level VSCs should not be used for studying fast dynamics in HVDC systems
  - Models assuming ideal power balance between AC and DC sides can only be used for studying phenomena at very low frequency

- Two cases of MMC modelling
  - Compensated modulation with Energy-based modelling
  - Un-compensated modulation with Voltage-based modelling

Energy-based model

Voltage-based model

Definition of subsystem interfaces

Workflow for generating the small signal model

Definition of subsystem interfaces
Aggregated participation factor analysis

- Approach proposed for identifying interactions in an interconnected system
  - An interaction mode is defined as an eigenvalue having participation $p_i$ higher than a threshold $\phi$ from both parts of the interconnected system
  - Interaction modes identified as shown below for $\phi = 0.20$
  - Close correspondence can be identified between identified interaction modes and eigenvalues that are significantly influenced by the interconnection

\[
W_{ij} = \sum_{i,j} W_{ij}
\]

MEM-based point-to-point transmission scheme

- Modes associated with the cable are quite quickly damped
- One oscillatory mode and one real pole are slightly dependent on operating conditions
- System is stable and well-damped in the full range of expected operating conditions

Interaction modes – MMC-HVDC point-to-point scheme

- More interaction modes compared to case with 1L VSC
  - In total 14 eigenvalues - 12 oscillatory modes (6 pairs) and two real poles.
  - A first group is defined as those well damped oscillatory modes (real part smaller than -200).
  - A second group of interaction modes is found much closer to the imaginary axis
    - Oscillatory mode (39-40)
    - Two real eigenvalues (48 and 49)

Time-domain verification of point-to-point MMC scheme

- Variables of small-signal model can accurately represent the nonlinear system model for variables at both terminals

DC voltage controlled terminal

- Balanced participation from the two converter stations
- High participation from the cable in the fastest modes
- Dominant participation from the DC voltage controlled terminal in oscillatory modes
- Low participation from the cable, especially for the two real poles
- Depending on the eigenvalue, one station will have a higher participation
Participation Factor Analysis of Interaction Modes

- The fast oscillatory modes (8-9, 10-11, and 14-15)
  - Related to dc voltages at both cable ends
  - Associated with cable dynamics
- Modes 21-22 and 25-26
  - "DC-side" interactions
  - Almost no participation from the AC-sides
  - Associated with the MMC energy-sum \( w \) and the circulating current \( i_c \)

Main conclusions related to interaction analysis

- Small-signal eigenvalue analysis can be utilized to reveal the properties of modes and interactions in the system
  - Participation and sensitivity of all oscillations and small-signal stability problems can be analyzed
  - Suitable for system design, controller tuning and screening studies based on open models
- Aggregated participation factor analysis can reveal interaction between different elements or sub-systems
C1) Met-ocean conditions

Assessing Smoothing Effects of Wind Power around Trondheim via Koopman Mode Decomposition, Y. Susuki, Osaka Prefecture University

An interactive global database of potential floating wind park sites, L. Frøyd, 4Subsea AS

Offshore Wind: How an Industry Revolutionised Itself, M. Smith, Zephir Ltd
Assessing Smoothing Effects of Wind-Power around Trondheim via Koopman Mode Decomposition

Yoshihiko Susuki (JP)
Fredrik J. Raak (JP)
Harold G. Svendsen (NO)
Hans C. Bolstad (NO)

EERA DeepWind’2018
January 17

Outline of Presentation

• Introduction
  – About JST Project / Why Smoothing Effect?
• Koopman Mode Decomposition (KMD)
  – Brief summary of nonlinear time-series analysis
• KMD-based Quantification of Wind-Power Smoothing
  – Definition and simple example
• Application to Wind-Data around Trondheim
  – Synthetic wind-power output
  – Quantification result
• Conclusion

Purpose and Contents

Quantifying Smoothing Effects of Wind-Power around Trondheim via Koopman Mode Decomposition

1. Introduction of Koopman Mode Decomposition (KMD)
2. Review of KMD-based Quantification
3. Application to Measured Data on Wind-Speed around Trondheim
   – Newly reported in this presentation

Outline of Presentation

• Introduction
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• Wrap-Up

Smoothing Effects of Wind-Power

• Reduction of fluctuations in wind-power by aggregation
• Importance of its assessment (or quantification) for managing large-scale introduction of wind power:
  – Large-term use --- planning w/ use of in-vehicle batteries
  – Short-term use --- controlling turbines / maintaining power quality

Koopman Mode Decomposition (KMD)

Novel technique to decompose multi-channel, complex time-series into modes with single-frequencies, conducted directly from data.

\[ \{g_0, \ldots, g_m\} \]

Koopman Eigenvector, determining freq./damping

\[ g_k = \sum_{j=1}^{m} \lambda_j \mathbf{V}_j = \sum_{j=1}^{m} \chi_j \mathbf{V}_j + \eta_{m} \]

Koopman Mode, determining amplitude/phase

KMD-based Quantification (1/3) -- Derivation

\[ P_k = \sum_{i=1}^{N} \lambda_i^k \hat{v}_i \quad k = 0, \ldots, N \]
\[ P_{\text{tot}, k} = \sum_{i=1}^{m} \sum_{j=1}^{m} \hat{v}_i \hat{v}_j = \sum_{i=1}^{N} \lambda_i^k \hat{v}_i \]

Total Power by aggregation

\[ \text{KMD of Wind-Power} \]

KMD-based Quantification (2/3) -- Definition

KMD of Wind-Power (again):

\[ P_k = \sum_{i=1}^{N} \lambda_i^k \hat{v}_i \quad k = 0, \ldots, N \]
\[ \hat{v}_i = A_i \alpha_i \]

Complex-valued vectors

Proposed Index:

\[ \text{coh}_{k, \text{KMD}} = \frac{1}{m(m-1)} \sum_{i=1}^{m} \sum_{j=1}^{m} |A_i | |A_j | \cos(\phi_{ij}) \]

- Total sum of similarity for every pair of components of a single Koopman mode
- Index computed for each single frequency
- Generalization of the conventional Power Spectrum Density (PSD)-based index

KMD-based Quantification (3/3) -- Example

\[ x_1(t) = \alpha_1 \sin(2\pi f_1 t) + b_1 \cos(2\pi f_2 t) \]
\[ x_2(t) = \left\{ \begin{array}{l} \alpha_2 \sin(2\pi f_1 t + \phi) + b_2 \cos(2\pi f_2 t + \phi) \quad f_1 = 2f_2 \frac{f_2}{T} = \frac{T}{2} \end{array} \right. \]

Data on Aggregated Wind-Power

Measurement Data around Trondheim

- 92-days long time-series of hourly wind speeds
  - 10 meters above ground / Mmean value for last 10 minutes before time of observation
- Converted into wind-power (in per-unit) via the static nonlinear power curve below

Data on Aggregated Wind-Power

Three Hypothetical Wind-Farm Sites

Outline of Presentation

- Introduction
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- Wrap-Up
Original Data and Reconstructed Data via KMD

![Graph showing original data and reconstructed data via KMD]

Summary and Take-Home Messages

Quantifying Smoothing Effects of Wind-Power around Trondheim via Koopman Mode Decomposition (KMD)

1. KMD enables an extraction of dominant feature w/ clear time-scale separation directly from complex wind-power data.
2. KMD enables a quantification of smoothing effects of wind-power around Trondheim — how the smoothing is engineered by the choice of locations.

Table 1. Variance of total power P and reconstructed time-series via KMD P

<table>
<thead>
<tr>
<th>Case</th>
<th>P_k (U)</th>
<th>P_k (U)</th>
<th>P_k (U)</th>
<th>P_k (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>#1 and #2</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Case 2</td>
<td>#1 and #3</td>
<td>0.11</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>Case 3</td>
<td>#2 and #3</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Lower Value of Variance!

Quantification Result

- More smoothing archived in high frequencies
- Better smoothing engineered in Case 1, consistent with the variance test

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Thank You for Your Attention!
Overview of database

- 100 < Water depth < 300 (Deep draught floater)
- Mean wind speed > 9.5 m/s @ 100 m elevation
- Distance to infrastructure (population) < 200 km
- Sorted by nearby population density

Metocean - A more complex case

Consider the following case:
- Long term motion analysis of a passive turret moored FPSO

How it works:
- FPSO orients with direction of wind, current and waves, but mostly wind and current
- Motions are largest in waves from side
- Swells common with directions offset from local wind direction

Proper analysis requires:
- Distribution of simultaneous:
  - Vessel heading,
  - Wind, current and wave directions,
  - Wind wave and swell Hs and Tp

Metocean typically provides:
- 2D Hs - Tp scatter
- Independent wind, wave, current distributions

Example - A proper analysis approach

Find FPSO heading from satellite photos

Develop heading model

Process local weather time series from global weather hindcast data

Numerical analysis of combined long term distribution

\[ \theta = f(U, C, W) \]
Building the database:

Global sea wind and wave hindcast
Copernicus CMEMS:
• GLOBAL_ANALYSIS_FORECAST_WAV
  _001_023
• WIND_GLO_WIND_L4_NRT_OBSERVATIONS_012_004

Global sea water depth
British Oceanographic Data Centre:
• GENERAL BATHYMETRIC CHART OF THE OCEANS (GEBCO)

Geonames.org:
• Coordinates and population of world cities with population > 15000

What can it do
Example: Global data – Mean Wind
Mean wind speed at 10 m elevation (m/s)
Generated using E.U. Copernicus Marine Service Information

What can it do
Example: Global data – Mean Hs
Mean significant wave height (m) contours
Generated using E.U. Copernicus Marine Service Information

What can it do
Example: Global data – Mean Tp
Mean wave peak period (s)
Generated using E.U. Copernicus Marine Service Information

What can it do
Example: Global data - Wave energy map
Mean wave energy contours (kW/m wave crest)
Generated using E.U. Copernicus Marine Service Information

Floating wind locations:
(First example revisited)
• 100 < Water depth < 300 (Deep draught floater)
• Mean wind speed > 9.5 m/s @ 100 m elevation
• Distance to infrastructure (population) < 200 km
• Sorted by nearby population density

Relative density of nearby population

Generated using E.U. Copernicus Marine Service Information
Floating wind locations:

- 100 < Water depth < 300 (Deep draught floater)
- Mean wind speed > 9.5 m/s @ 100 m elevation
- Distance to infrastructure (population) < 200 km
- Sorted by annual mean wind speed (10 m elevation)

Who can use it:

- All data sources are publically available
- In principle, the combined product can be made publically or comercially available:
  - E.g. complete global coverage
  - Or on a location by location basis
  - Full hindcast time series
  - Or aggregated properties (e.g. mean, max)
- Access and availability is not yet decided
  - (Remember, dataset more or less a bi-product of another work)
  - Please make contact if the dataset can be useful for you – we will arrange something!
  
Example of possible data views:

- With the magic of Python (and some patience)

Simple aggregated views:
- Sorting based on mean or annual max: Hs, Tp, wind speed, water depth, etc...
- Ranking sites by some fitness function (high wind, low wave, near shore, etc)

Utilizing the full hindcast:
- Seasonal waiting times for marine operation with some operational limit (Hs, Tp, Wind speed)
- Power factor of some specific wind turbine (based on binning of wind speeds)
- Estimated site LCOE (with some clever cost model)
- Etc...

Proposed use cases:
- Resource assessment
- Feasibility studies
- Preliminary site optimization / analyses
- Operational/maintenance planning
- Etc...

Who can use it:

- All data sources are publically available
- In principle, the combined product can be made publically or comercially available:
  - E.g. complete global coverage
  - Or on a location by location basis
  - Full hindcast time series
  - Or aggregated properties (e.g. mean, max)
- Access and availability is not yet decided
  - (Remember, dataset more or less a bi-product of another work)
  - Please make contact if the dataset can be useful for you – we will arrange something!

Sources – Wind/wave hindcast:

- This study has been conducted using E.U. Copernicus Marine Service Information
- Copernicus CMEMS: http://marine.copernicus.eu/

Sources – Water depth:

- GEBCO 2014 water depth database:
  - https://www.bodc.ac.uk/data/hosted_data_systems/gebco_gridded_bathymetry_data/
Sources — Population density:

- Geonames.org database of world cities with population > 15000
  
  http://download.geonames.org/export/dump/cities15000.txt

Share ideas, move forward
Offshore Wind
How an Industry Revolutionised Itself

Matt Smith
Offshore Lidar Expert
EERA DeepWind 2018

A disclaimer!

Please note:

- As many of you know, I am a Lidar salesperson!
- This is less of a scientific and more of an overview of various activities that occurred over the last decade that have revolutionised the wind industry.
- I hope it’s an interesting story and many of you will have been involved along the way.
- Feel free to leave now on this basis or submit your thoughts to me after the presentation!

So how did the offshore industry differ?

Not so much ‘how’ but ‘why’ - the then only available option for wind resource assessments offshore – an offshore met mast:

- Massive “at risk” investment if looking at installing a new platform
- Mast anemometry is difficult to achieve at modern offshore hub heights
- Increased interest in the full rotor swept area
- Ongoing maintenance, health & safety inspections and calibration of anemometry
- Impact on Levelised Cost of Energy
- Time to get to results – planning etc.
- Representation of wind resource at a single point across the site
- … Floating Wind!

Let’s just say Lidar was knocking on an already open door!

15 years ago... in a galaxy not so far away

The response? Go and prove yourselves! And at this time, there were no clear standards, no IEC guidance on remote sensors, no authorities in this area.

Project needs and adoption

What did that open door look like?

- Time to market for a disruptive technology vs. rate of industry growth
- Quality of wind data
- Quantity of wind data
- Data across a site
- Health & Safety improvements
- Through-life risks – Day 1, Day 100, Day 1000, Day 10,000?
- Through-life costs
The first movers / innovators

ZephIR Lidars were the first to be deployed offshore on fixed platforms.

2005, Beatrice Platform, North Sea
2006, NaKun, Hecate Strait
2010, Robin Rigg, Solway Firth
2014, Bell Rock Offshore Windfarm, Dundee

Roadmap to acceptance

NaKun demonstrated a low-cost Lidar platform could work but only went part of the way to reducing cost and time to water.

But in 2010 Deepwater Wind demonstrated that a floating Lidar could work just as well.

Just 3 years later - 2013 – a range of floating Lidars were tested and validated as part of the UK’s Carbon Trust Offshore Wind Accelerator (OWA) programme.

Knowing the time pressures / scale of offshore wind growth, the OWA published a set of recommendations to give the industry the formal framework needed to accelerate the commercial deployment of the technology while standards were being developed. The IEA build on this work to offer recommendations for using floating lidar including wider considerations: H&S, Deployment, Moorings,..

Commercial deployments of floating Lidars accelerated significantly!

The rise of the truly floating Lidar

The industry pulls sideways

Lidar is now accepted as a proven technology by the wind industry from a practical, contractual and, increasingly, from an industry standards’ perspective.

Perfect timing as the hub height and swept area of offshore wind turbines surpasses using mast anemometry as an economically viable option.

• Use of Lidar for Resource Assessment demonstrates Best in Class data
• Reliability demonstrated on industry firsts with floating lidars going into their third year of continuous operation
• Known boundaries of use through research studies – important! And help to define new areas of research and validation
• Cost advantages demonstrated on projects coming to fruition
• …Look at the US market, there are no masts and most sites will progress without one

Operational Assessments

No platform to use from met mast?
Deploy Lidars on wind farm substations!

Merkur Offshore Windfarm

• Lidar is coupled to met data acquisition systems, data is transmitted to client platform for access.
• Data is integrated with SCADA systems.
• Lidar is used for power performance analysis using hub height measurements.
• Combined with other sensors to support helicopter landing ops including personnel winching.

Research Council of Norway

One of the earlier publicly available assessments was conducted here in Norway.

Financed by NRC and Statoil with in-kind support from Fugro Oceanor, UiB and CMR.

This directly led to the further development and adoption of the Fugro Seawatch buoy (based 5 minutes walk from this event)
Energisation and Start of Warranty

Offshore, contractual power curve verification tests according to IEC 61400-1-12 standards remains highly impactful – as they require the installation of a met mast and the only permits the testing of one turbine in such large arrays.

The March 2018 update permits the combination use of Lidar and mast and whilst this has progressed the use of verification methods it still requires significant investment offshore to accommodate the requirements.

Nacelle mounted Lidar delivers accurate measurements, across multiple turbines, at a significantly lower cost point, with high availability and low uncertainties.

The shear size and cost of offshore wind projects is focussing more on commercial agreements than IEC standards whereby development wind specialists are defining power curve verification tests with the turbine OEMs.

Many leading OEM’s now accepting a nacelle mounted Lidar power curve test (Lidar calibrations, test methodologies and result analysis has already been defined)

23/01/2018

The industry has revolutionised itself

In the space of 5 years since the first OWA analysis of offshore Lidars, there is adoption for fixed and floating platforms with Lidar, across all project phases – something not even achieved onshore yet!

What next?

• The full range of capabilities offered by Lidar in any format continues to be developed and validated.
• This will lead to further pull sideways in to other applications and project phases.
• The industry continues to drive down LCOE.
• Safety First across everything we do.
• Innovation time is getting faster.

23/01/2018

2017 – Look at where we were

London, 18 July 2017. Leading wind measurement experts gathered in London claimed that LidARs have been replacing met masts to become the sole wind measurement tool used for offshore resource assessment and power curve verification purposes

Deutsche Windguard, Klaus Franke, Project Engineer: “Application of Nacelle Based Lidar for Offshore Power Curve Tests”

ECN, Hans Verheef, Project Leader Measurements: “Offshore wind development with standalone Lidar”

EDF EN, Cedric Dall’Ozzo, Senior Wind Resource Assessment Engineer: “Reducing uncertainties: vertical profiler, floating, scanning and nacelle Lidars”

MHI Vestas, Tue Hald, Senior Specialist: “Power curve verification with nacelle two-beam Lidar on V164-8.0 MW”

RES, Iain Campbell, Technical Analyst and Wind Resource Manager: “Lidar: Just better than a mast?”

Siemens, Pedro Salvador, rotor Performance engineer: “From R&D to Plug & Play: 8 years of nacelle Lidar experience”

SSE, Gordon Day, Offshore Wind Analyst: “Replacing masts with Lidar for financing and performance assessment”

UL DEWI, Beatriz Canadillas, Senior Researcher: “Offshore Wind Lidar since 2009: from R&D to commercial applications”

23/01/2018

Construction Monitoring

Block Island Windfarm

ZephIR 300 was installed on Fred. Olsen Windcarrier’s Brave Tern jack-up vessel - used to compare wind speeds against those measured with the main boom tip crane wind sensor

Measurements were used as a “live” instrument during all phases of construction and specifically during critical points of component lift. 5 second live data was displayed with wind shear curves in the user interface.

Where wind behaviour was difficult to explain i.e. when wind at the tip of the crane was lower than on the crane A-frame, or bridge level, ZephIR 300 could identify and explain the difference across the full lift height.

During WOW (Waiting-On-Weather) downtime, ZephIR 300 provided a very accurate picture of the wind conditions to enable effective decision making.

During high winds when the crane was in the boomrest, ZephIR 300 was used to confirm when it was worth lifting the crane out of the boomrest again before making any unnecessary movements.

Today we see Lidar included as standard in offshore tenders for vessels operating on wind farm construction

23/01/2018

It certainly hasn’t finished yet.....
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C2) Met-ocean conditions

Wind conditions in a Norwegian fjord derived from tall meteorological masts and synchronized doppler lidars, H. Agustsson, Kjeller Vindteknikk

Complementary use of wind lidars and land-based met-masts for wind characterization in a wide fjord, E. Cheynet, University of Stavanger

Simulation and observations of wave conditions in Norwegian fjords, B.R. Furevik, Meteorologisk institutt
Wind conditions in a Norwegian fjord derived from tall meteorological masts and synchronized doppler LIDARs

Hálfdán Ágústsson, Martin S. Grønsleth, Ola Kaas Eriksen, Ove Undheim, Finn K. Nyhammer, Øyvind Byrkjedal, Kjeller Vindteknikk, Norway
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Ferry free E39 in West/Norway

- Eight fjords to cross
- Fjord widths 2-7.5 km
- Fjord depths 300-1300 m
- High and variable climate loads
- What are the appropriate design loads?

Extensive observational campaign

- A 50 – 100 m high met mast at ends of each crossing.
- Min. 4 years of 10 Hz obs. of 3D wind at 3-4 elevations in masts.
- Additional masts to investigate horizontal coherence
- Wave and current buoys
- Two pairs of synchronized LIDARs

Observational data in the open domain. Corroborated by up to 10 years of meso-scale (500 m X 500 m) and CFD simulations (~100 m X ~100 m).
LIDARs on east side of fjord

**Descriptive planar scans**


Dolly & Donald

---

**LIDAR Doppler principle (4)**

- The moving aerosols induce an optical frequency change of the backscattered LASER pulse: Doppler effect.
- The Doppler shift is proportional to the radial wind speed.
- A radial wind speed $V_r$ of 1 m/s induces a Doppler shift of about 1.2 MHz

---

**LIDAR vs mast**

- Wind speed and direction
- LIDAR signal to noise ratio

---

**Resolutions? Physical VS Display resolutions**

- Physical resolution: Atmospheric probe length
- Display resolution: Distance between two successive gates

- Physical resolution < Display resolution

---

**LIDAR vs mast**

- Wind speed and direction
- LIDAR signal to noise ratio

- Good signal
Radial wind speed - LIDAR vs mast

True wind - LIDAR vs mast

Example turbulence spectra - Mast vs LIDAR
1 Hz / 10 Hz temporal resolution, 20 min period. 50.3 m.

MAST
Along wind, U
Transverse, V
Vertical, W

LIDAR
Along wind, U
Transverse, V
Vertical, W

Example turbulence co-spectra - Mast vs lidar
1 Hz / 10 Hz temporal resolution, 20 min period
Vertical co-coherence of along wind variation U, 50.3 m vs. 31.8 m

MAST

LIDAR

Example turbulence co-spectra - Mast vs lidar
1 Hz / 10 Hz temporal resolution, 20 min period
Vertical co-coherence of transverse wind variation V, 50.3 m vs. 31.8 m

MAST

LIDAR
Concluding remarks

- First results and examples from four LIDARs observing atmospheric flow in Halsafjorden since autumn 2017.
- The synchronized LIDARs are a part of the extensive observation campaign pertaining to the ferry-free E39 project.
- Detailed description of key parameters of atmospheric flow away from the shore, here surrounded by complex orography.

Acknowledgments

Important contributions and expert advice from:

- Michael Courtney and Guillaume Lea from the Danish Technical University
- Jasna Bogunovic Jakobsen and Etienne Francois Cyprien Cheynet from the University in Stavanger
Goal: To characterize the wind conditions in the middle of a 5 km-wide and 500 m-deep fjord

Possibilities:
- To use Doppler wind lidars [1]
- To use traditional wind masts on the seaside

Here, the lidar instruments only measure the horizontal flow

Main questions

Are the lidar records and anemometer measurements consistent?

To what extent are the wind velocity data on the shores of the fjord affected by the surrounding terrain?

Location of the Sensors (1/2)

Location of the Sensors (2/2)

Each contour line corresponds to a height of 5 m

MW1 and MW2: One sonic anemometers at 33 m, and two at 49 m above the ground.

ME1 and ME2: Sonic anemometers at 12 m, 32 m and 48 m above the ground.
Overall wind conditions (1/2)
Record period: Mai-June 2016

Lidar records
(z = 25 m above sea level)

Anemometer records on MW1
(z = 33 m above ground)

Record period: Mai-June 2016

Overall wind conditions (2/2)

Lidar records
(z = 25 m above sea level)

Anemometer records on ME1
(z = 32 m above ground)

Record period: Mai-June 2016

Mast MW1 vs Lidar records (1/3)
Relative difference on the mean wind velocity

Mast MW1 vs Lidar records (2/3)
Relative difference on the mean wind direction

Mast MW1 vs Lidar records (3/3)
Relative difference on the standard deviation of the along-wind velocity component

Mean incidence angle
Relative difference on the mean wind velocity

\[ \epsilon_W^W = 1 - \frac{\overline{W} (MW1 at 33 m)}{\overline{W} (Lidar)} \]

\[ \epsilon_{\alpha_W} = 1 - \frac{\sigma_W (MW1 at 33 m)}{\sigma_W (Lidar)} \]

\[ \epsilon_{\sigma_{\alpha_W}} = 1 - \frac{\sigma_{\alpha_W} (MW1 at 33 m)}{\sigma_{\alpha_W} (Lidar)} \]
Conclusions

1. The lidar records are consistent with those from the anemometers for a limited number of sectors only.

2. There is a clear influence of the local topography on the anemometer measurements.

3. The combined use of Doppler Wind lidar with Sonic anemometer data is relevant for wind characterization in a wide fjord.
Simulation and observations of wave conditions in Norwegian fjords

Birgitte R. Furevik, Konstantinos Chryssakis (MET Norway), Øyvind Byrkjedal, Húfnún Ágústsson, (Kjeller Vindteknikk), Lasse Leneeth, (Fugro Oceanor)

Measurements in Sulafjord - unique data set, freely available

Tall met-masts with sonic wind measurements in three heights, around 100m, 70m and 50m (red)
Wave buoys (A, B, D) and under water rigs for oceanographic measurements (blue)
Data are available on http://thredds.met.no/thredds/obs.html

Outline

- Background and motivation
- Observations
- Operational forecast models of wind and waves
  - Setup and forcing
  - Verification
- SWAN hindcast
  - Setup for ferry-free E39
  - NORA10
  - Atmosphere model
- Results
  - Statistics
  - Case
- Summary

Forecast models at MET

Ferry-free E39

Verification of forecasts in Sulafjord

AROME wind speed

WAM significant wave height

800m

4km
Wave hindcast using SWAN

- Version 41.10
- 3rd generation wave model
- Temporal and spatial development of 2D wave spectra in each grid point
- Variable wind input and spectra on the open borders
- 36 directions, 31 frequencies (0.04-Hz)
- Domain with 250mx250m grid cells nested into outer grid (1kmx1km)
- Wind from Kjeller Vindteknikk hindcast with WRF (500mx500m)
- Border spectra from the Norwegian wind and wave hindcast (10-11km)
- January 2007 – June 2017
- Hourly output of integrated wave parameters (Hs, Tp, Tm02, Peak dir., Mdir etc.) and spectra in selected locations

Norwegian Reanalysis 10 km (NORA10)
dynamical downscaling of ERA-40 and standalone wave hindcast

Atmospheric component – HIRLAM 10 km:
  - ERA-40 on boundaries (6-hourly)
  - 40 levels: temp, wind, humidity, cloud water
  - Surface: pressure
  - Blended with ERA-40 in interior (digital filter)
  - Maintain large-scale features
  - Preserve mesoscale features (polar lows)
  - Sequence of 9-hour model runs (3 hourly data)
  - 24h x 400 grid points

Wave component – nested WAM-model
  - WAM 50 km forced by ERA-40 winds
  - WAM 10 km forced by HIRLAM10 winds
  - 2D spectrum: 24 by 25 directional/frequency bins
  - September 1957 onwards

Wind input to SWAN

- WRF nested 1500m to 500m

Wave model setup with SWAN

- SWAN 41.10 – with van der Westhuysen (2007) dissipation
- 1 January 2007 – 30 June 2017
- 1km to 250m nesting
- Wind from WRF (500m), Spectra on border from NORA10

WAM and SWAN wave height

Similar performance
Slight overestimation in Hs

SWAN wave height – statistics

Relation between overestimation in Hs and high wind speeds
AROME and WRF wind speeds

Too weak winds in AROME at low wind speeds

Wave statistics in Sulafjord

Example of uncertainty due to parameter-based wave spectra

Wave spectra

Model may be right for the wrong reason

AROME compared to satellite SAR

Weak winds and low correlation in fjords

Summary and comments

- Large measurement program in several fjords in mid-Norway
- Data freely available, but access is temporarily closed at the moment (until May)
- Working to improve wave and wind modelling in the fjords
- Three PhD students started last year
- Poster on wind shear by Midjiyawa Zakari outside

Final report from project FjordWind funded by the Norwegian Space Center
D1) Operations & maintenance

Wind Turbine Gearbox Planet Bearing Failure Prediction Using Vibration Data, S. Koukoura, University of Strathclyde

Data Insights from an Offshore Wind Turbine Gearbox Replacement, A.K. Papatzimos, University of Edinburgh

Further investigation of the relationship between main-bearing loads and wind field characteristics, A. Turnbull, University of Strathclyde

Damage Localization using Model Updating on a Wind Turbine Blade, K. Schröder, University of Hannover
Wind turbine gearbox planet bearing failure prediction using vibration data

Sofia Koukoura, James Carroll & Alasdair McDonald
Department of Electronic & Electrical Engineering
University of Strathclyde, Glasgow
sofia.koukoura@strath.ac.uk
EERA DeepWind’18, Trondheim, 17 - 19 January 2018

Paper Objective
Create an automated failure prediction framework for wind turbine gearbox bearing faults. This framework is based on two stages:

- **Vibration Analysis and Feature Extraction**
  - Find trends at varying times prior to component failure.
  - Extract features based on those trends.

- **Classification**
  - Use features as inputs to a pattern recognition model.
  - Learn the behaviour characteristics of the trends for prognosis of degradation and failure prediction.

Motivation
- Wind turbines are machines that operate under harsh conditions and therefore components fail before the end of the expected life of the turbine.
- Catastrophic failures increase O&M costs and consequently the LCOE.
- Predictive maintenance is applied in wind turbine industry so that O&M actions are optimised accordingly.

**Figure:** Wind Turbine on fire.

Bearing Vibration Theory
- Bearing faults introduce a shock that excites high frequency resonances.
- Bearing signatures:
  - Masked by other components in the gearbox.
  - Stochastic.
- Planetary stage hard to diagnose.
- Ball passing frequency (repetition frequency) depends on:
  - speed $(n)$.
  - dimensions.

$$BPF = \frac{n}{2} \left(1 + \frac{d}{p} \cos(\theta)\right)$$

Average Repair Time and Costs in Offshore Wind
Average repair times and costs for major replacements are given per failure category [2].

**Figure:** Average repair time.

- The top three average repair times occur in the hub, blades and gearbox.
- The gearbox has the highest average cost per failure.
- From the CM perspective, a wind turbine gearbox consists of three major components: bearings, gears and lubricant.

Vibration Signal Pre-processing
- Deterministic (gear) and random (bearing) components need to be separated.
- This can be done using an adaptive filter.
- Envelope analysis - often used in bearing diagnostics - demodulates the signal in a high frequency band.
- In order to choose the right band, spectral kurtosis indicates how kurtosis is distributed in the frequency domain and shows the impulsiveness of the signal. Thus it can be used as a filter [3].

**Figure:** Adaptive filter.

- **Figure:** Spectral Kurtosis [3].
- **Figure:** Envelope Analysis.
Classification: k Nearest Neighbours

- kNN classifier classifies unlabelled observations by assigning them to the class of the most similar labelled examples [1].
- Non-parametric and instance-based.
- k is tuned using cross-validation.
- Features used as input in a bearing fault case could be energy around ball passing frequency and its harmonics.

![Example of kNN classification](image)

Signal Processed Vibration Data Analysis Results

- Envelope spectra of vibration signal for similar loading conditions. Only 3s of each signal are used and where they are assumed to be stationary.

![Envelope Spectra](image)

**Wind Turbine Considered in This Study**

- Faulty bearing
- Gearbox internal structure

![Faulty bearing](image)  ![Gearbox internal structure](image)

Wind turbine rated between 2.5-3.5MW.
- Double planetary stage gearbox, commonly found offshore.
- Inner race spalling
- 95 samples collected at various times prior to failure (2.5 years to 1 week before).
- Acceleration data collected on a sampling rate between 20-30kHz for 10-15s. 2

*Ranges are given for confidentiality reasons.

**Classification Results**

<table>
<thead>
<tr>
<th>Predicted Class</th>
<th>1-2 months</th>
<th>5-6 months</th>
<th>healthy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Class</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-2 months</td>
<td>75%</td>
<td>18%</td>
<td>7%</td>
</tr>
<tr>
<td>5-6 months</td>
<td>21%</td>
<td>69%</td>
<td>9%</td>
</tr>
<tr>
<td>healthy</td>
<td>6%</td>
<td>12%</td>
<td>19%</td>
</tr>
</tbody>
</table>

**Conclusion and Future Work**

**Conclusion**

Low speed stage bearing faults may not be diagnosed through raw vibration data.
- Signal processing can help enhance the bearing fault impulses.
- Given sufficient samples, features can be extracted from vibration data and given as inputs to machine learning classification models.
- Classification models are able to classify signals based on their health state, useful for diagnosis and prognosis.
Conclusion and Future Work

Future work

- Other types of classification methods, e.g. neural networks could increase accuracy.
- Order tracking techniques can improve the filter and the overall accuracy results.
- More historic data samples will train more robust models.

References I

1. Christopher M Bishop
   Pattern recognition and machine learning (information science and statistics)
   Springer-Verlag New York.

2. James Carroll, Alasdair Mc Donald, and David McMillan
   Failure rate, repair time and unscheduled O&M cost analysis of offshore wind
   turbines.

3. Robert B. Randall and Jerome Antoni
   Rolling element bearing diagnostics tutorial.
   Mechanical systems and signal processing, 25(7):485-520, 2011.
1. Introduction and Motivation

Introduction - EDF Group Offshore Assets
- Teesside Offshore Wind Farm
  - 27 2.3MW turbines
  - 1.6 km offshores
  - 7-15m water depth
  - Installation completed in June 2013
- Blyth Demonstrator Project
  - 5 Vestas 8.3MW turbines
  - Future assets
  - Totaling 1.5GW

Motivation
- Gearbox replacement @ Teesside
- Gearboxes are designed to last for the lifetime of the asset - IEC 61400-4
- Majority of onshore and offshore wind turbines have a geared drivetrain
- Currently largest installed wind turbine (V164-8.0 MW) has a gearbox
- Early detection by OEM
  - Reduce downtime
  - Reduce component lead time
  - Understand component reliability
- Perform future fault prediction and diagnosis

2. Wind Turbine Gearbox Failures

Most common failure causes [3, 4]:
- Fundamental gearbox design errors
- Manufacturing or quality issues
- Underestimation of operational loads
- Variable and turbulent wind conditions
- Insufficient maintenance

Most common failure locations [4-8]:
- HS Bearing
- IMS bearing
- Planet bearing

Most common failure modes:
- Micro-pitting [9]
- Tooth breakage [10]
- Pitting [11]
- Scuffing [11]
2. Wind Turbine Gearbox Failures

- SCADA
  - Temperature, pressure, vibration, current, rotational speed, etc.
- CMS
  - Vibration
    - Sampling in time instances
    - Pre-processed (Envelopes, FFTs, Cepstrum, RMS, etc)
  - Oil Particle Counter

3. Wind Turbine Gearbox Monitoring

- 3 stage planetary/helical gearbox

4. Data Pre-processing

Filtering

- SCADA Alarms + maintenance log timestamps have been removed that include:
  - Yaw, Pitch, Generator, Electrical, Grid, Sensor failures, Environmental conditions, Maintenance operations

5. Failure Detection & Diagnosis

- Gearbox Oil Temperature vs Active Power
- Gearbox Oil Temperature vs (Rotor Velocity)^2
- Gearbox Oil Temperature Bins
5. Failure Detection & Diagnosis

CMS

Planet Bearing Envelope

Planet Bearing FFT

6. Data-Driven Models

SCADA

- “Healthy” state for data 4 months after replacement (orange)
- “Warning” state for data 4 months prior to replacement (blue)

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Specifications</th>
<th>True Pos. (Healthy)</th>
<th>True Positive Rate (Warning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVM</td>
<td>Gaussian, Scale:0.26</td>
<td>97%</td>
<td>92%</td>
</tr>
<tr>
<td>Ensemble</td>
<td>Bagged Trees, Split: 10, learners: 30</td>
<td>96%</td>
<td>91%</td>
</tr>
<tr>
<td>KNN</td>
<td>Mahalanobis, NN=10</td>
<td>96%</td>
<td>92%</td>
</tr>
<tr>
<td>Decision Tree</td>
<td>Gini's index, max number of splits: 400</td>
<td>95%</td>
<td>86%</td>
</tr>
<tr>
<td>SVM</td>
<td>Quadratic, box constraint: 1</td>
<td>93%</td>
<td>81%</td>
</tr>
</tbody>
</table>

CMS

- Not constantly monitored systems
- Automation of forecasting models
- Autoregressive model for RMS signal
  - Predicted same slope for 26 out of 27 turbines

Conclusions

- Planet stage bearing spalling on a 3-stage 2.3MW turbine gearbox
- Similar studies investigated catastrophic gearbox failures
- Identify and diagnose the failure by using SCADA and CMS data
  - Temperature readings
  - RMS vibration
- Data driven models to predict future failures

Future Work

- Further test the models in other failure modes and wind turbine models
- Investigate the environmental conditions' impact on the results

7. Conclusions and Future Work

Conclusions

- Planet stage bearing spalling on a 3-stage 2.3MW turbine gearbox
- Similar studies investigated catastrophic gearbox failures
- Identify and diagnose the failure by using SCADA and CMS data
  - Temperature readings
  - RMS vibration
- Data driven models to predict future failures

Future Work

- Further test the models in other failure modes and wind turbine models
- Investigate the environmental conditions' impact on the results
References


Questions

Alexios.Koltsidopoulos@edfenergy.com

Acknowledgement:
This work is funded by the Energy Technology Institute and the Research Council Energy Programme as part of the IDCORE programme (grant EP/J500847).
Further investigation of the relationship between main-bearing loads and wind field characteristics

A Turnbull¹, E Hart¹, D McMillan¹, J Feuchtwang¹, E Golysheva² and R Elliott²

¹University of Strathclyde, Glasgow, UK
²Romax InSight, Nottingham, UK

Motivation

- Main-bearings seldom reach design life of roughly 20 years.
- Some failing after as little as 6 years [1].
- Reasons for this are still not fully understood.
- Cost associated with the repair is expensive.
- As we move further offshore, these effects are amplified due to cost of support vessels, weather and access restrictions.

Research aims

1. Create a simple model which focuses on realistic input loads from which cause and effect can be easily separated.
2. Understand loading across wind turbine operating envelope and link this to wind field conditions.
3. Provide evidence to support claims that axial to radial load ratio is a key factor in main bearing failure.

Aeroelastic model

- GH Bladed software used for aeroelastic wind turbine simulations.
- Wind field characteristics
  - 4 wind speeds (10, 12, 16, 20m/s)
  - 2 shear profiles (shear exponent 0.2, 0.6)
  - 3 turbulence intensities (high, med, low as described in IEC standards [2])
- 144 different wind fields to define operating envelope.
- Hub forces and bending moments extracted in all three degrees of freedom.

Drivetrain model

- Drivetrain models generated for both double and single main bearing configuration.
- Separate model for radial and axial loads.
- Lengths and spring stiffness’s determined by ROMAX Insight FEA modelling software for commercially available wind turbine of rated power around 2MW.
- Bearing type dependent on the configuration.
Results – Peak axial loads

Results – Peak radial loads

Results – Load ratio

Effects of shear profile

Effects of turbulence intensity

Conclusions

• Strong link between wind conditions and main bearing loads for both configuration – wind shear highest sensitivity factor.

• In general it can be observed that the double bearing configuration experiences a significant decrease in load ratio.

• Highest load ratio occurs in the single main bearing configuration in high shear and low turbulent conditions.

• With single main bearing configuration observed to fail more often, evidence suggests there could be link with load ratio.
Potential impact of research

- Develop ways in which to bring the relationship into design stage when calculating component life, steering away from traditional methods of steady cyclic loading.

- Use relationship as a factor to support decision making of wind turbine type/configuration at particular site.

Thank you for your attention, any questions?
Structural Change Identification at a Wind Turbine Blade using Model Updating

K. Schröder, S. Grove, S. Tsiapoki, C.G. Gebhardt and R. Rolfes

I. Motivation

II. Optimization based model updating

III. Rotor blade test

IV. Model updating at the rotor blade
   1. Damage localization
   2. Ice accretion

V. Conclusion and Outlook

Content

Motivation

- Remote location
- Rotor blades: costly and time-consuming repair
- Ice accretion: - Risk of ice throw
  - Undesired loads

Minimization of the deviation

Global optimization algorithm:
- Simulated Quenching

Local optimization algorithm:
- Sequential Quadratic Programming

Deviation between numerical model and measured data

Quantification of the „difference“ between model and measurement

Modal parameters

- Eigenvalues
- Mode shapes

Transmissibility functions

Minimization of the deviation

\[
\min_{\theta} \varrho(\theta) \\
\text{subject to } \varphi_i(\theta) \geq 0 \quad \forall i \in I
\]
Rotor blade test

- Hammer excitation
- 12 measurement channels
- Ice mass
- Damage

Numerical validation

Stiffness reduction

\[
\min \theta \quad \text{subject to} \quad \theta_i \geq 0.5 \quad \forall \ i \in \theta \\
\theta_i \leq 1.01 \quad \forall \ i \in \theta \\
\sum_i (1 - \theta_i) \leq 0.5
\]

Numerical validation - Model Parameters

- Rectangular Cross Section
- Known: EI and mass
- 26 Timoshenko beam elements
- Clamping at blade root
- Material damping

Numerical validation - Transmissibility Functions
Ice accretion

- 4 steps
- Variation of density
- Optimization problem: 
  \[ \min_{\theta} \phi(\theta) \]
  \[ \text{mit } \theta_i \geq 0, 0.39 < i < 7 \]
  \[ \theta_i \leq 1.15, 1 \leq i \leq 7 \]

- Step 3: 14.4kg at 32m-33m and 33m-34m

Conclusion & Outlook

**Conclusion**
- Updating in numerical examples and for ice quantification successful
- Minimization using global two-step optimization algorithm
- No success for damage localization using measured data
- Modal parameters superior to transmissibility functions

**Outlook**
- Investigate more advanced metrics for model updating
- Application to changing conditions (in situ)

Ice localization – Modal Parameters

- Correct Localizations in runs 1, 3, 7, 9 und 11
- Verification using objective function value
- Ice localization using modal parameters is possible

Ice quantification – Modal Parameters

- Investigate more advanced metrics for model updating
- Application to changing conditions (in situ)
D2) Operations & maintenance

Using a Langevin model for the simulation of environmental conditions in an offshore wind farm, H. Seyr, NTNU

The LEANWIND suite of logistics optimisation and full life-cycle simulation models for offshore wind farms, F.D. McAuliffe, University College Cork

Analysis, comparison and optimization of the logistic concept for wind turbine commissioning, M. Wiggert, Fraunhofer IWES
Using a Langevin model for the simulation of environmental conditions in an offshore wind farm

Helene Seyr and Michael Muskulus

January 18, 2018

Outline

- Introduction
- Methodology
- Data
- Results
- Conclusions

Data

ECMWF:
- Re-analysis
- 6h resolution
- Dogger Bank wind farm
- 37 years

Fino 1:
- Measurement from met-mast and buoy
- 10min/30min means
- Alpha Ventus wind farm
- 6 years

Introduction

- O&M (cost) optimization is focus of research
- Many simulation models/optimizations rely on artificially generated weather time series to test different strategies
- Novel approach to model significant wave height and wind speed
- Langevin process:
  - Equations fitted to the data
  - Used to generate artificial weather

Results I
Results II

Results V

Results III

Results VI

Results IV

Conclusions

- Langevin process is a good alternative
- Properties of waves represented very well (Distribution, Persistence)
- Higher sampling frequency → better model
- 2D Langevin process for correlation (?)
Thank you for your attention
The LEANWIND suite of logistics optimisation & full lifecycle simulation models for offshore wind farms

Presenter: Fiona Devoy McAuliffe

Project supported within the Ocean of Tomorrow call of the European Commission Seventh Framework Programme

EERA DeepWind’18 conference
Trondheim, Norway

Presentation overview

- Introduction
- Methodology
- Logistics optimisation models
- Financial simulation model
- Combined use
- Potential end-users

Introduction

Significant cost reductions to date:
Vattenfall’s 2016 offshore wind price bid of €49.9/MWh for the Kriegers Flak project set a record LCOE forecast of €40/MWh

Current and future challenges to maintain & surpass savings:
- Increased industry competition to find cost reductions
- New markets yet to achieve LCOE forecasts
- Sites further from shore in deeper waters and harsher conditions
- Larger turbines and farms with new equipment and logistical requirements
- Facing the unknown – the decommissioning phase

Introduction

Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments

OBJECTIVE: to provide cost reductions across the offshore wind farm lifecycle and supply chain through the application of lean principles and the development of state of the art technologies and tools.

- UCC is coordinator
- 31 partner organisations
  - 52% industry partners
  - Representing 11 countries;
- €14.9m total funding;
- €10m EC funding;
- 4 year duration
  - December 2013-November 2017

Introduction

Modelling is a safe and cost-effective way to evaluate and optimise operations. However, there is a lack of comprehensive decision-support tools, detailed enough to provide insight into the effects of technological innovations and novel strategies.

They can reduce costs by identifying potential savings and fostering effective decision-making for a wide range of stakeholders.

LEANWIND developed a suite of logistics and financial tools, which can optimise the entire supply-chain and simulate the full wind farm lifecycle, providing in-depth cost and time analysis.
LEANWIND developed a suite of logistics and financial tools, which can optimise the entire supply-chain and simulate the full wind farm lifecycle, providing in-depth cost and time analysis.

### Methodology

#### Logistics optimisation models

<table>
<thead>
<tr>
<th>Prior to/post port</th>
<th>Installation</th>
<th>O&amp;M</th>
<th>Decommissioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTPIns</td>
<td>PTPOM</td>
<td>IntDis</td>
<td></td>
</tr>
<tr>
<td>At port</td>
<td>Portlay, PortIns</td>
<td>PortOM</td>
<td>PortDis</td>
</tr>
<tr>
<td>To/from offshore site</td>
<td>VMIns</td>
<td>VMOM</td>
<td>IntDis</td>
</tr>
</tbody>
</table>

- **Prior to/post port**: manufacturing, transportation, storage, and assembly.
- **At port**: selection of the port(s) for each lifecycle phase & optimal layout (installation phase).
- **Supply to/from offshore site**: transportation of parts to/from the port to the site.
Finding cost-optimal solutions for the maritime logistic challenges

**Components to install** i.e. the number of components to be installed per day.

**VMOM - port to site models**

VMOM - Based on the generated corrective & preventive maintenance patterns, the model chooses the **number and type** of vessels needed in the offshore transport system.

[Diagram showing VMOM with inputs and outputs]

**IntDis – integrated dismantling model**

Vessel schedule and flow of components for decommissioning. The objective function is to minimise the total cost of activities.

[Diagram showing IntDis with layout and flow]
Financial simulation model

**Financial model interface**

**Inputs**
- Farm details
- Strategy (installation, O&M, decommissioning)
- Vessel fleet...

**Outputs**
- Energy production & availability
- Time/activity
- Cost/activity
- Total cost breakdown
- Financial indicators...

---

**O&M module**

**Key Outputs**
- Full project timeline i.e. duration of activities across the lifecycle
- Energy yield and availability
- Detailed breakdown of:
  - capital & installation costs (CAPEX)
  - operation & maintenance costs (OPEX)
  - decommissioning costs (DECEX)
- LCOE, NPV, IRR and payback period
- Cashflow with project profit and loss sheet
- Balance sheet to evaluate debt and equity

---

**INST module**

Scope: the turbine, foundation, substation, substation foundation, export and inter-array cabling. The user can specify or use a pre-defined selection of assets. Different operations are then associated with the installation of each asset e.g.

<table>
<thead>
<tr>
<th>Installation method</th>
<th>Lifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower parts, nacelle and hub pre-assembled</td>
<td>5</td>
</tr>
<tr>
<td>Blades and hub pre-assembled</td>
<td>3</td>
</tr>
<tr>
<td>Nacelle, hub and 2 blades (blunt nose) pre-assembled</td>
<td>4</td>
</tr>
<tr>
<td>Tower parts and nacelle, hub and 2 blades (blunt nose) pre-assembled</td>
<td>3</td>
</tr>
<tr>
<td>Pre-assembled</td>
<td>1</td>
</tr>
<tr>
<td>Pre-installation substrate</td>
<td>0</td>
</tr>
</tbody>
</table>
DCM module

Scope: Turbine and foundation.

Inputs: The component (e.g. blades, nacelle, gearbox etc.) and order in which they are dismantled; component materials and weight; operation durations; up to three destination ports; landfill or recycling centre locations; number of technicians; vessels available etc.

Outputs: Costs; time and revenue e.g. salvage

Validation: Results for the C-Power OWF were €513,000 per MW within range estimated by DNV GL of €200,000-€600,000/MW (Source: Chamberlain K 2016 Offshore Operators Act on Early Decommissioning: New Energy Update).

Conclusion

1. Comprehensive and complementary set of logistics and financial models
2. Can foster significant cost-savings in the industry through effective decision-support.
3. Fill a significant gap in the current models available.
4. They can be used individually or together to optimise and simulate the full supply-chain and lifecycle of an OWF project.
5. Combined use can save considerable computational time.
6. Designed primarily for the project planning and design phase but also useful during operational period.
7. They can address current and future challenges faced by a wide range of stakeholders.

Combined use – the benefits

Different objectives and methodologies but complementary:
- Very time-consuming to optimise a scenario with simulation models & not humanly possible to consider all possible solutions.
- The optimisation models determine the key supply-chain configurations and the financial models examine the top ranking options in further detail.
- Simulation models can assess a scenario in detail and the Monte Carlo method considers the uncertainty of key risk factors e.g. failures and weather.
- Combined they can obtain the most economically viable and time efficient solutions to a wide range of logistical and strategic issues.

Potential end-users

See you in Cork!
- WESC 2019 -
  June 17th – 20th
  Cork, Ireland

Thank you very much for your attention.
Welcome
WIND · ASSURING CONFIDENCE THROUGH COMPETENCE
Analysis, comparison and optimization of the logistical concept for wind turbine commissioning
Dr. Marcel Wiggert

Agenda & Goals

- Topic and challenges
- Introduction WaTSS concept
- Approach
- Case study: Commissioning
- Conclusions

Topic

- Title: Analysis, comparison and optimization of the logistical concept for wind turbine commissioning
- Conditions:
  - Weather risk of the WTG installation
  - Optimization of the number of commissioning teams
  - Comparison of 3 different logistical concepts
- Decision criteria: lowest cost and risks

Information Profile

- Weather Parameters
- Project Schedules
- Boundary Conditions
- Cost and Risk Optimization
- WEATHER TIME SERIES
- PROJECT SCHEDULES
- BOUNDARY CONDITIONS
- WEATHER RISK PROFILE
- CONTINUOUS ANALYSIS PROCESS → EASY WORK FLOW INTEGRATION

Challenge
WaTTS – Method
Weather Time Series Scheduling

Consideration of:
- Task sequence
- Contingencies in guidelines
- Different weather restrictions
- Calculation of project durations and their probabilities

Virtual Project Test Center
Yearly Simulation

Virtual Project Test Center
Continuous Simulation

Simulation Concept

1. Installation dates of the wind turbines per analyzed year
   Goal: Definition commissioning start dates
2. Success of the commissioning work for every day
   Goal: Definition of the turbine accessibility
3. Post Processing: e.g., MS Excel or MATLAB
   Goal: Analyzing the scenarios
   a. Calculation of the commissioning duration per turbine and year under consideration of weather and resource constraints
   b. Calculation of the required vessel days and costs
   c. Evaluation and presentation of the results
Case Study: IWES Baltic

Introduction

Weather parameters:
- Significant Wave Height (hS)
- Wind Speed (U)

Boundary conditions:

- Number of turbines: 90
- Rent distance: Allan
- Start date: 2020-01-01
- Commissioning (1 Team): 36h/Turbine (net)
- Team costs: 1,000 Euro/day
- Opportunity costs: 3,000 Euro/day per turbine
- Vacation rate: 20% (5/26-20)

Assumptions:
- hS = 1.5m
- 3 Teams on board; 12h/7 days
- Costs: 4,000 €/d
- 8h/day on turbine

- hS = 1.5m
- 20 Teams; 24h/7 days
- Costs: 20,000 €/d
- 10h/day on turbine

- hS = 2.5m
- 20 Teams; 24h/7 days
- Costs: 24,000 €/d
- 10h/day on turbine

Case Study: IWES Baltic – Results

WTG Installation Strategy

Scenario Analysis

Costs (P50)

Risk Profile

Conclusion

- Post processing extends capabilities of the WaTSS method
- Approach to consider the availability of transport (resources) for the commissioning teams
- Important to consider risks and cost simultaneously
- Case Study: “IWES Baltic”
**Acknowledgements**

Fraunhofer IWES is funded by the:

- 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
- Federal Republic of Lower Saxony
- Free and Hanseatic City of Hamburg

**References**

- Adwen
- BASF
- e.on
- Enercon
- Gamesa
- GE Energy
- Nordex
- RENEN
- Senvion
- Vattenfall
- WEG

**Background**

**Detailed Information**

**Detailed Analysis**

**Risk Efficiency**

Thank You For Your Attention

Any questions?

marcel.wiggert@iwes.fraunhofer.de
Primary and Secondary Weather Risks
Duration vs. Start Day

Weather Impact – Example Accessibility
(July – December)
E1) Installation and sub-structures

Floating offshore wind turbine design stage summary in LIFESSO+ project, G. Pérez, TECNALIA

A comprehensive method for the structural design and verification of the INNWIND 10MW tri-spar floater, D. Manolas, NTUA

Reducing cost of offshore wind by integrated structural and geotechnical design, K. Skau, NGI and NTNU

Catenary mooring chain eigen modes and the effects on fatigue life, T.A. Nygaard, IFE
Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m

The research leading to these results has received funding from the European Union Horizon2020 programme under the agreement H2020-LCE-2014-1-640741.

LIFES50+ project overview

First stage of the project: design and evaluation of four concepts, for three sites, 10 MW reference wind turbine and considering 500 MW wind farm.

WP1 Concepts Design

WP1 - Concept development and optimization

M1-M40
176 PM, 23% of total budget

Work organized in three stages:

1. Design Basis
2. Concepts design
3. Selected concepts optimization

Stage 2 focused on the concepts design for their assessment

WP1 Concepts Design

MS1: Design Basis ready for starting design (June-November 2015)

Task 1.1 Definition of the target locations: business cases.
Results: D1.1 Oceanographic and meteorological conditions for the design (Public)

Task 1.2 Wind turbine specification.
Result: D1.2 Wind turbine models for the design (Public)

Public deliverables available on the project’s web site www.lifes50plus.eu

WP2 Concept evaluation

WP4 (Numerical tools)

WP5 Industrialization

WP6 (Uncertainty/Risk)

MS2: Concepts design ready (December 2015 – March 2017)

Task 1.3 Concepts development for a 10MW wind turbine.
Results:
- D1.3 Concepts design
- D1.4 Wind turbine controller adapted to each concept
- D1.5 Marine operations
- D1.6 Upscaling procedure (Public)

Task 1.4 Concepts design assessment.
Result: D1.7 Information for concepts evaluation

MS4: Phase 1 qualification performed

WP3 Experimental validation

WP1 Concept development

WP7 (Design practice)

Outline

- LIFES50+ project overview
- WP1 Concepts Design
- Design Basis
- Concepts Design process
- Conclusions & Challenges

15. januar 2018
Design Basis

- Oceanographic and meteorological conditions for the three selected sites.
  - Site A (moderate met-ocean conditions), offshore of Golfe de Fos, France
  - Site B (medium met-ocean conditions), the Gulf of Maine, United States of America
  - Site C (severe met-ocean conditions) West of the Isle of Barra, Scotland

Concepts Design process

Concepts design, driven by the information required for the evaluation:
- KPIs
- LCOE and LCA figures. Forms for 50 wind turbines wind farms -3 excel sheets-, one wind turbine -1 excel sheet- and 5 wind turbines -1 excel sheet-
- Uncertainty forms for each of the sites.
- Information for risk analysis.

LIFESS50+ Design Process conditioned for the concepts assessment and evaluation:
1. Onshore benchmark to validate WT models.
2. 'Design references’ to select an justify the Load Cases for each site and each concept.
3. Design Briefs to validate the design process and the assumptions.

Numerical tools used in LIFESS50+ consortium

Concept developers followed their own design procedures and codes, validated at different levels in the consortium, to ensure a common framework for their assessment.
Concepts Design process

Concept developers considered all the design topics:
- Sizing and structural design – subtask 1.3.1-
- Mooring design – subtask 1.3.2-
- Aero-hydrodynamic simulations – subtask 1.3.3-
- Adaptation of the WT controller – subtask 1.3.4-
- Analysis of marine operations, including manufacturing strategy – subtask 1.3.5-

Several information submissions were established in order to facilitate the concepts evaluation and improve concepts design.

Evaluation Committee gave feedback after each submission, and requested more information for specific topics.

Conclusions & Challenges

Specific to LIFES50+ work in the first stage of the project.
- It was difficult to establish the framework to assess and compare different types of substructures – technical point of view, KPIs-

General to the floating offshore wind design.
- Precise and clear information from the very beginning: design basis.
  - Wind turbine features and restrictions for the substructure developer
  - Site information
  - Standards
- Close collaboration between the different parties involved in the wind farm development, in order to ensure a global view of the project.
- Design and simulation tools adapted to each project stage.

Concepts Design results

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<th>Lead Beneficiary</th>
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Contact:
german.perez@tecnalia.com

The research leading to these results has received funding from the European Union Horizon 2020 programme under the agreement H2020-ICT-2016-1.640741.
A comprehensive method for the structural design and verification of the INNWIND 10MW tri-spar floater

DI Manolas, CG Karvelas, IA Kapogiannis, VA Riziotis, KV Spiliopoulos and SG Voutsinas

EERA DEEPWIND'18, Trondheim, January 18th 2018

Outline

- Scope
- Numerical Tools
- Method for detailed design and verification
- INNWIND 10MW tri-spar concrete floater
- Conclusions

Numerical Tools

SAP2000: 3D FEM Solver
General purpose commercial software for analyzing any type of structures.
- Solution: Static, frequency domain and time domain
- Elements: Beam, shell thick, solid
- Design is fully integrated for both steel and concrete members, based on American or European standards

hGAST: hydro-servo-aero-elastic tool
General in-house simulation platform for analyzing the fully-coupled dynamic behavior of WT
- Simulates all support structures
- Modules
  - Dynamics: Multi-body formulation
  - Elasticity: beam theory
  - Aerodynamics: BEM or Free wave
  - Hydrodynamics: Potential theory or Morison’s equation
  - Moorings: dynamic modeling
  - Control: variable speed/pitch
  - Environmental Excitation according IEC

freFLOW: Hybrid integral equation method
General in-house hydrodynamic solver for analyzing and designing floating structures
- Solution: 3D Laplace equation in frequency domain
- Method: BEM – indirect formulation with constant source distribution
- Radiation condition: Matching with Garrett’s analytic solution
- Provides: Exciting loads, Added mass & damping coefficients, RAOs, total hydrodynamic loads and total hydrodynamic pressure

Scope

- Cost effective method for floater detailed design and verification
- 3D “complex” geometry (i.e. semi-submersible, tri-spar etc)
- Concrete
- Account for ULS and FLS
- Environmental excitation (wind & wave/current)
- Realistic modeling
- Application: INNWIND 10MW tri-spar concrete floater
Method for detailed design and verification

- **SAP2000**
  - Pressure field on floater's wet surface
  - Tower base loading vector

- **freFLOW**
  - hGAST

- **hGAST** (IEC DLCs)
  - ULS: maximum loading
  - FLS: lifetime PSD

- **freFLOW**
  - Input: Preliminary design
  - Checking (stress level)
    - ULS: capacity ratios (max \( \sigma \) / material yield \( \sigma \))
    - FLS: pressure PSD
    - ULS: max pressure
      - Simultaneously applied
      - Generating the max moment at critical points

**INNWIND 10MW tri-spar concrete floater**

- **WT: DTU 10MW RWT**
  - Rotor D: 178.3m
  - Hub Height: 119.0m
  - Tower base: 25.0m

- **Floater: tri-spar concrete**
  - Concrete: 11478tn
  - Steel: 1138tn
  - Ballast: 15653tn
  - Total: 28268tn

- **Water Depth**: 180m
  - Catenary mooring lines

**DLCs definition for time domain simulations**

<table>
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<th>Wave</th>
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<td>ESS</td>
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<tr>
<td>6.2</td>
<td>EWM</td>
<td>SSS</td>
<td>3</td>
<td>41.8</td>
<td>0</td>
<td>0, 30</td>
<td>1.25</td>
</tr>
</tbody>
</table>

*Maximum tower base loading applied on the tri-spar floater (WT) at 13m/s, Hs=10.9m, Tp=14.8s, SF=1.35.*

Lifetime PSD of tower base fore-aft moment, Weibull C=11/s, k=2.
Detailed design and verification
- Heave plates (HP): steel → concrete
- Concrete Column (CC): reinforcement
- Connection (steel legs-concrete columns)
- Steel Tripod

Materials:
- Steel: S450, t=0.0564m
- Concrete: C50/60, t=0.40m
- Rebar: Reinforcement

Reinforcement (DLC1.6 - max pressure)
- CC Vertical: Ø25/180
- CC Horizontal: Ø20/250
- HP Radial: double Ø36/65
- HP Horizontal: double Ø36/75

Tripod Design Modifications
- Bracket width (5.64m → 4.62m)

Local reinforcements
- Central cylinder: t=0.0564-0.175m
- Brackets: 3 diaphragms
- Legs: 4 diaphragms
- Legs: t-top =0.0564m
- gamma connection: triangular plate

ULS verification: capacity ratios at critical positions
(DLC1.6 at 13m/s, Hs=10.9m, Tp=14.8s)

Connection | Capacity ratios | I | II |
---|---|---|---|
1. Central Cylinder -Horizontal Leg Connection | 0.64 | 0.68 |
2. Horizontal Leg-Vertical Leg Connection | 0.26 | 0.28 |
3. Vertical Leg - Inclined Rods Connection | 0.64 | 0.78 |
4. Inclined Rods | 0.46 | 0.54 |
5. Ties | 0.08 | 0.09 |

FLS verification: 20 years damage ratios at critical positions

Connection | D-N curve parameters | Damage | Ratio |
---|---|---|---|
1. Central Cylinder - Horizontal Leg | B2 | 16.856 | 5 | 0.31 |
2. Horizontal Leg at inclination point | C | 16.320 | 5 | 0.83 |
3. Horizontal Leg - Vertical Leg | B2 | 16.856 | 5 | 0.99 |

**I: max pressure, II: max moment at gamma-connection

A comprehensive method for floater detailed design and verification has been presented.

The isolated floater is analyzed in 3D FEM solver, by performing static (ULS) and frequency domain (FLS) simulations

WT loads: hydro-servo-aero-elastic tool (hGAST)

Wave loads: frequency domain potential solver (freFLOW)

Application on INNWIND 10MW tri-spar floater; the present designs seems to be FLS driven.
Outlook

- More design loops (mainly for FLS)
- Detailed modeling for mooring lines connection point
- Verification of the method vs fully coupled analysis

Thank you for your attention

Acknowledgements:
This work was funded by the European Commission under INNWIND.EU project. The authors would like to thank all INNWIND WP4 colleagues and especially José Azcona, Frank Lemmer and Feike Savenije who provided expertise that greatly assisted this research.
REDWIN – REDucing cost in offshore WINd by integrated structural and geotechnical design

EERA DEEPWIND January 2018

Load frequencies and eigen frequency

Blade load frequencies (1P and 3P)
- Wind spectrum (Kaimal)
- Wave spectrum (JONSWAP, $H_s = 2.4$ m)

Turbines:
- DTU 10 MW
- Vestas V164 (8MW)
- Siemens SWT-6.0-154 (6MW)
- Siemens SWT-3.6-107 (3.6 MW)
- Vestas V90 and V91 (3MW)

The importance of the foundation


The importance of the foundation


REDWIN

- 4-year research project
- Sponsors: NFR, Statoil, Vattenfall, Statkraft
- Partners: NGI, NTNU, IFE, Dr. Tech. Olav Olsen
- 16 mill NOK
- Bottom fixed OWT
- 1 year left

The importance of the foundation


Integrated dynamic analyses

- Aero dynamics
- Hydro dynamics
- Struktrual dynamic
- Turbine controller (pitch)
- Soil/foundation respons

REDWIN model principles

- Application oriented models, such that the choice of model appear intuitive.
- User interface understandable for practitioners.
- General models, adaptable to different ground conditions.
- The models have to work in time domain analyses.

Geotechnical involvement

Current practise

- p-y springs (API, PISA) for monopiles
- Linear elastic springs for shallow fundations
Monopiles

Redwin model 1
Distributed 1D model to be applied to any DOF.

Redwin model 2
HM-loading

Redwin model 3
VHM-loading

Soil – support model

Foundation – structure interface

Gravity based foundations

Foundation – structure interface
Summary and conclusions

- The models and tools developed in REDWIN seem to contribute to more accurate descriptions of foundations in design.
- They include damping, which is often neglected.
- The knowledge of soil and site can be better utilized in design.
- Improved accuracy reduce costs.
- Currently working om cost reduction effects in more detail.

Thanks to:
The Norwegian research council, Statoil, Vattenfall og Statkraft

...and co-authors and contributors!

And thanks for your attention!
Catenary Mooring Chain Eigen Modes and the Effects on Fatigue Life

Tor Anders Nyaard and Jacobus de Vaal, IFE
Morten Hvidt Madsen and Håkon Andersen, Dr.techn Olav Olsen AS
Jorge Altuzarra, Vicinay Marine Innovacion

Catenary Mooring

- Soft station-keeping, keep platform within envelope for current, drift forces and mean rotor thrust
- Should ideally not restrict platform first order wave motions. Platform inertia is averaging wave force peaks
- Restoring force by geometric stiffness of the catenary shape
- Possible conflict with maximum deflection of power cable

Baseline Fatigue Case

- OO-Star Wind Floater with 6MW rotor
- 100m water depth, anchor radius 750m
- 147mm chain with marine growth and hydrodynamic coefficients according to DNV-GL recommendations
- Wind (16 m/s), waves (Hs 3.7m) and current (0.15m/s) aligned with upstream mooring line

Effects of Water Depth

- Decreasing water depth gives decreasing catenary effect and increasing force amplitudes for given floater motions
- Sharp rise in force when the entire chain is lifted off the seafloor

Contributions to fatigue, Rainflow Counting, 1

- Identify turning points
- Split in full- and half cycles
- Each cycle has a stress range, that together with the S-N curve and Miner rule corresponds to fatigue damage
- Each stress cycle also has a frequency
- We have binned the stress cycles according to stress range and frequency, and can then sort out the contributions from different frequencies and stress ranges
Important contributions to fatigue from frequencies up to 0.3Hz
Important stress ranges 2 – 10 MPa
Frequencies above 0.12Hz contribute to about 40% of the fatigue damage
These low stress ranges are commonly ignored on dry land. The standard does not recommend a cut-off in sea-water

Models
- 3DFloat(IFE), SIMA(Sintef Ocean) and OrcaFlex(Orcina)
- Morison’s equation on relative form.
- Nonlinearities: Co-rotated in 3DFloat and SIMA, direct specification of element matrices in global frame in OrcaFlex
- Chain eigen modes by linearization and eigen analysis in SIMA, and by bandpass-filtering of time-domain motions in 3DFloat

Eigen Modes Identification
- Single mooring line similar to baseline, but with constant properties. The results are similar, but the eigen frequencies change somewhat
- Pre-tension by positioning of fairlead to obtain 2000kN tension at fairlead.
- Apply irregular waves as in baseline case.
- Compare peaks in PSD plots with eigen analysis and forced fairlead motion results.
- Visualization of motions

Single Line, Fixed Fairlead, Waves Only
- Standard deviation of stress is around 0.2MPa, compared to 2MPa for FLS with floater, waves, current and wind.
- Stress due to direct wave loading on line is therefore not important compared to floater motions
- This case is useful also for identifying possible eigen frequencies

Forced Motion Sweep 0.15 – 0.6 Hz
3DFloat
- Single mooring line, pre-tension 2000kN
- Harmonic inline horizontal motion of fairlead, increasing frequency slowly from 0.10Hz to 0.6Hz (shown from 0.15Hz due to initial transient)
- Amplitude is decreased with increasing frequency to keep peak acceleration of fairlead constant
- Peaks at approx. 0.19Hz, 0.33Hz and 0.42Hz
- This corresponds relatively well with the waves only case shown in the previous slide

Forced Motion of Fairlead
Comparison of models
Horizontal harmonic motion, 10cm amplitude
**Forced Motion of Fairlead, 2**

Horizontal harmonic motion, 10cm amplitude

- Good agreement for 0.15 and 0.17Hz
- 0.19 and 0.21Hz are close to eigen frequency at 0.2Hz, some differences and sensitivity to model parameters
- Some differences at 0.23 and 0.25Hz, increased influence of inertial loads.
- At 0.2Hz, the dynamic response compared to the quasi-static response correspond to an amplification factor of 10

**Conclusions**

- Computations of fatigue in a catenary mooring system applied at intermediate water depth with three state-of-the-art integrated models show similar results, that are very different from quasi-static mooring line characteristics
- A mode with three half-waves between fairlead and touchdown shifts the response to higher frequencies than what is expected from the wave spectrum
- Important contributions to fatigue are from stress ranges 2 – 10 MPa and frequencies up to 0.3Hz
- More experimental results are needed for model validation; previous successful validation was at a water depth corresponding to 200m, and with different influence of inertial forces relative to gravity and drag forces.

---

**Model validation against experiments**

- The models OPASS (CENER) and 3DFloat (IFE) were successfully validated, but this was for 200m depth, and no marine growth.
- We have not found experimental results corresponding to our case study.

**Acknowledgements - Innovative mooring systems**

- Scope: Innovative Solutions for Shallow Water Mooring Systems
- RCN project under ENERGIX, project number: 256364
- Project Responsible: Dr.techn. Olav Olsen
- Partners: IFE, Statoil, Rolls Royce, Vicinay, OTS, Aibel, Servi
- External advisors: DNV-GL, NGI, FMGC

**Sensitivity Studies**

- Sensitivity studies on parameters regarding numerics and load models, with respect to response, in particular above 0.12Hz.
- Limited sensitivity, except the inertial coefficient in the Morison equation and marine growth.
- Extreme current can limit the response through increased viscous damping
E2) Installation and sub-structures

A numerical study of a catamaran installation vessel for installing offshore wind turbines, Z. Jiang, NTNU


Integrated conceptual optimal design of jackets and foundations, M. Stolpe, Technical University of Denmark
A numerical study of a catamaran installation vessel for installing offshore wind turbines

Zhiyu Jiang
January 18, 2018

Postdoctoral researcher
Department of Marine Technology
Centre for Marine Operations in Virtual Environments (SFI MOVE)
Norwegian University of Science and Technology

Outline

1. Introduction
2. The catamaran installation concept
3. Numerical simulation
4. Conclusion

Background

Water depth:
- <20m
- 20-40m
- 50-70m
- >50-100m

Capital expenditure of offshore wind

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<th>Item</th>
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<tr>
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<td>Decommissioning</td>
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<tr>
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<tr>
<td>Turbine</td>
<td>15.2%</td>
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<tr>
<td>Balance of plant costs</td>
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Installation methods - foundation

- Tripod installation using a jack-up vessel
- Jacket installation using a floating vessel
- Monopile installation

Installation methods - rotor blade

- Bunny ear
  - Valenfall
- Full rotor
  - Dong Energy
- Single-blade installation
  - Fred Olsen Wind Carrier

Installation methods - full assembly

- Saipem 7000
  - Statoil AS
- Novel installation vessel
  - Ullstein AS

Outline

1. Introduction
2. The catamaran installation concept
3. Numerical simulation
4. Conclusion

The catamaran installation concept

L.I. Hatledal et al. (2017)

Purpose of numerical simulation

- Design and testing of novel installation methods
- Response-based prediction of limiting operational conditions
- Online decision support for offshore installations

Challenges of the concept

- Hydrodynamics
  - hydrodynamic coupling, sloshing, viscous effect
- Structural dynamics
  - coupled motion modes, mechanical coupling
- Automatic control
  - station keeping of the vessel, active ballast system motion tolerance and control, landing force control
Installation procedure

Properties of the catamaran

- Length overall (m): L
- Breath moulded (m): B
- Spacing between monohulls at waterline (m): Lwet
- Draft (m): T
- Displacement mass (tonnes): D
- Vertical center of gravity above baseline (m): KG
- Transverse metacentric height (m): GM

Monitoring the relative motions

Outline

1. Introduction
2. The catamaran installation concept
3. Numerical simulation
   - Time-domain simulation
   - Frequency-domain simulation
4. Conclusion

Properties of the spar

- Diameter at top (m): L
- Diameter at waterline (m): W
- Draft (m): T
- Displacement mass (tonnes): D
- Vertical center of gravity above baseline (m): KG
- Vertical fairlead position below waterline (m): Zf
- Body origin in global coordinate system: (X,Y,Z)
- Total length of mooring line (m): L
- Diameter of upper chain segments (mm): D
- Diameter of lower chain segments (mm): D

Time-domain simulation

WADAM: Hydrodynamic analysis of the two-body system

HAWC2: Calculation of the wind forces on the turbine assemblies

SIMO: Time-domain coupled analysis
Catamaran with dynamic positioning system; spar with mooring lines; sliding grippers between catamaran and spar
Modelling of the hydrodynamics

Frequency-domain approach

1. Hydrodynamic analysis of the two-body system

2. Short-term motion prediction of the mating point by using Response Amplitude Operators

Modelling of the sliding grippers

Magnitude of the pitch RAOs

Environmental conditions

Hs=2.0 m Tp=6, 8,...,12 s  β=0, 90 deg
Results - relative surge motion

Hs=2.0 m, β=0 deg

Results - relative roll motion

Hs=2.0 m, β=90 deg

Conclusion

• A numerical modelling approach of the catamaran installation concept is introduced.

• Future work is needed for implementing the active heave compensator, dimensioning of the catamaran, active ballast system, etc.

Acknowledgements

• Zhen Gao
• Karl Henning Halse
• Peter Christian Sandvik
• Zhengru Ren
Instrumenting the Gravity base foundations for the Blyth Offshore Demonstration wind farm

January 2018 | Jonathan Hughes and Paul McKeever

ORE Catapult

Our Vision:
Abundant, affordable energy from offshore wind, wave and tide

- Reduce the cost of offshore renewable energy
- Deliver UK economic benefit
- Engineering and research experts with deep sector knowledge
- Independent and trusted partner
- Work with industry and academia to commercialise new technologies

ORE Catapult Business Model

The catapult network:
A long-term vision for innovation & growth

The Blyth Offshore Demonstrator Wind farm

- 5x 8.3MW turbines
- 6.5km off the coast of Blyth
- 194.5m Tip Height (AOD)
- Approx 40m Water Depth
Installation of GBFs at Blyth – Satellite Imagery

FSFound Project Aims
To validate the FS GBF solution as an alternative solution to energy provision by proving that FS GBF performs as intended and can be installed cost-effectively;

• To conduct a range of simulation and modelling studies to minimise the uncertainties and inefficiencies in the deployment process and in various weather windows;
• To compare the actual costs and performance with the cost-benefit analysis performed;
• To assess structural response to extreme and fatigue loads on the FS GBF and compare theoretical loads with real ones;
• To establish the effect of cyclic loadings on the seabed through monitoring and measurement and verify/calibrate models for differential settlements in the soil;
• To establish the optimal seabed preparation requirements (i.e. minimum preparation depth).

Caisson Pressure Sensors
• Upper sensor mounted near vent (sea reference)
• Lower sensor mounted near top of slipform
• 3 sets of 2 mounted at 120° spacing
• 4Hz sample rate

Aims of the measurement campaign?
1. Validation of the design, including input to verifying simulation models
2. Providing feedback to the design limits of the structure, such that an updated life expectancy can be calculated (if required)
3. Understanding the interaction between:
   - GBF and Seabed (e.g. settlement)
   - GBF and WTG (e.g. modal interaction, load transfer)
   - GBF/WTG combination and the Environment (e.g. wind/wave misalignment loads)
   - Effect of internal divisions on the displacement of the caisson outer walls
4. Provide inputs to the design of a Structural Health Monitoring system for GBF system
5. Provide inputs to the cost model, in the form of estimated O&M OPEX costs
6. Provide a platform for the development of a prognostic methodology for NDT of GBFs

Inclination and Mode Shapes
• High stability servo inclinometers
• Measurement range of +/-14.5°
• Resolution of 0.001°
• Positioned to match ANSYS AQWA modelling nodes
• Positioning is critical to interpretation of data
Load Paths

- Initially aimed to install SGs into Concrete, however not possible
- Structure can be analysed through load paths rather than direct loads
- Bending, Compression and Torsion are independently assessed
- Loads measured above and below “Wet Joint” – calculation of loads into caisson roof
- Loads measured at field weld to establish effect of loads from turbine and torsional loads

Installation Challenges

- Vertical installation requires significant additional time and risk management
- Installing delicate sensors; to fine tolerances; in the wet; hanging from a rope...
- Horizontal installation challenging without the ability to roll or traverse
- Location Referencing
- Novel and Evolving design
- Fitting research into a complex and time-critical construction project

Corrosion

- Structures are filled ballasted with sand and seawater flooded below LAT
- Water is expected to have slow transit rate through structure, leading to oxygen depletion
- Dissolved Oxygen sensors are installed to monitor
- Water level in shaft is monitored for comparison
- DO Sensors use dynamic luminescence quenching rather than an EC sensor

How close are models to their physical counterparts?

Connection and Protection

- Instruments are useless if they don’t work or give questionable data
- Welding and Bolting were not permitted by the designer
- All instruments are permanently bonded, but need a temporary method of attachment until the adhesive “grabs”
- Protection needed against ballasting force
- Protection against settlement
- Subsea-grade cables and connectors
- Full epoxy fill to instrumentation systems

Software Systems
Example Data – Inclinometer Profile

Planning for Analysis

- Flowcharts convert theory into algorithm for processing

Why is Research in a Commercial Project so challenging?

Commercial Ideals
- Strong “proven” technical solution
- Warrantable performance allowing for “tight” contracts
- No unexpected outcomes

Research Ideals
- Cutting Edge “novel” technical solution
- Project technical output comes before programme
- Unexpected outcomes are interesting (isn’t that why we do it?)

The best common outcomes only come through
- Close collaboration between practical and theoretical work
- Novel techniques but proven technologies and strong theoretical base
- Trial and error (more trials, fewer errors!)
Integrated design optimization of jackets and foundations for offshore wind turbines

Kasper Sandal
Chiara Latini
Varvara Zania
Mathias Stolpe

ABYSS – Advancing Beyond Shallow waters
funded by Innovation Fund Denmark

How to formulate a numerical optimization problem:
Let \( x \) be a vector of variables, where we want to minimize \( f(x) \)

Objective function

\[
\begin{align*}
\text{minimize} & \quad f(x) \\
\text{subject to} & \quad g(x) \leq 0
\end{align*}
\]

Constraint functions

How to design a jacket and its foundation with optimization:
Let \( x \) describe the design, \( f(x) \) the cost, and \( g(x) \) the engineering limits

Cost = Jacket + foundation mass

Objective function

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\begin{align*}
\text{minimize} & \quad f(x) \\
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Engineering limits:
1. Diameters & wall thickness
2. Fatigue limit state
3. Ultimate limit state
4. Soft-stiff frequency range

The optimization problem has very few design variables, but a high number of nonlinear constraints

- 24 design variables for the jacket
- 3 design variables for the foundation
- 7k constraints for each static load
  - Stress along all tubular welds
  - Shell buckling & column buckling
  - Foundation capacity
- 2 frequency constraints

This is how optimization can become a valuable tool for structural engineers in offshore wind

Design considerations

Optimal design problem

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The problem is implemented in the special purpose software JADOP (Jacket Design Optimization).

JADOP

- Mesh
- Loads
- Finite Element Analysis
- Sensitivity analysis
- Post-processing

Interfacing scripts

- fmincon
- GA
- IPOPT
- CPLEX
- Built-in solvers

The problem is implemented in the special purpose software JADOP (Jacket Design Optimization)

We make assumptions in the structural analysis which are suitable for the conceptual design phase:

- Timoshenko beam elements for the support structure
- Linear 6-dof response for each foundation
- 4 Damage equivalent loads for the fatigue limit state
- 3 Extreme static loads for the ultimate limit state
- Conservative analysis of column buckling
- Stress concentration factors in welded tubular joints

No safety factors are applied in the following examples.

For a given design problem (10 MW turbine, 50 m depth, piles), the total mass was minimized to 631 tons (in 5 minutes on a laptop).

JADOP has a parameterized mesh which makes it a quick task to modify for example the leg distance.

When support structures with different leg distance are optimized, jacket mass and foundation mass show opposite design trends.

The optimal leg distance will depend on for example the soil stiffness.

For a given design problem (10 MW turbine, 50 m depth, piles), the total mass was minimized to 631 tons (in 5 minutes on a laptop).
But several other aspects of the anchoring will also influence the design problem.

We have looked at:
- Piles & suction caissons
- Sand & clay
- Varying soil stiffness
- Different design procedures for piles

The design considerations are “translated” into an optimization problem, and it is now a quick task to generate design trends.

Structural optimization is used to automate the “well-defined” engineering tasks of conceptual support structure design.

The preferred leg distance now depends on the soil stiffness, and perhaps also the desired fundamental frequency.

With a tool like JADOP it is then quick & easy to investigate how input conditions influences the design.
F) Wind farm optimization

The DIMSELO Project (Dimensioning Sea Loads for Offshore Wind Turbines), F. Pierella, IFE

A savings procedure based construction heuristic for the offshore wind inter-array cable layout optimization problem, S. Fotedar, University of Bergen

Calibration and Initial Validation of FAST.Farm Against SOWFA, J. Jonkman, National Renewable Energy Laboratory

An Experimental Study on the Far Wake Development behind a Yawed Wind turbine, F. Mühle, NMBU
Wave models

- Deep water
  - Low steepness ($A/\lambda$) of the wave
  - Linear solution is satisfactory
- Shallow water
  - $h = 25m \sim 40m$
  - High steepness
  - Nonlinear effects
- Bottom-fixed wind farms are positioned at this depth

Diffraction of waves

- Large structures scatter incoming waves
- Leads to reduction in loads
- Important for large monopiles
  - $T = 2.5 \, s$
  - $h = 30 \, m$
  - $D = \lambda = 10 \, m$

Design calculations via integrated models

Current practice

<table>
<thead>
<tr>
<th>Fatigue</th>
<th>Extreme loads</th>
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</thead>
<tbody>
<tr>
<td>Kinematics model</td>
<td>Linear irregular waves</td>
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<tr>
<td>Load Model</td>
<td>Morison equation</td>
</tr>
<tr>
<td>Challenges</td>
<td>Non-linearity</td>
</tr>
<tr>
<td>Wave diffraction</td>
<td>Accuracy of non-linearity</td>
</tr>
</tbody>
</table>
Questions at the base of DIMSELO

Kinematic loads can drive the design

1. How conservative are standard kinematics and force models?

2. Are the better engineering models? Can they be used?

3. Can we quantify the consequences of applying them?

WP1
McCamy-Fuchs load model

WP2
Embedment of streamfunction waves

WP3
McCamy-Fuchs load model

WP1 Rainey slender body model

WP2 Wave Modeling

WP3 Aerodynamics VLR

WP1 Slender body models

WP2 Irregular 2nd order waves

WP3 Coherence of turbulence spectra

WP1 Large cylinders (First order Diffraction)

WP2 Embedment of nonlinear waves

WP3 6p and 2nd order bending moment interaction

WP1Scatter of waves by cylinder

WP2 Ratio of force predicted by Morison force model over MacCamy-Fuchs force model

WP2 Embedment of streamfunction waves

WP3 Use of the Hilbert transfer to calculate the embedment period

WP1 Standard: 50-yr wave «cut-and-paste» in irregular linear waves

DIMSELO Structure of the project:

Based on an energy balance methodology and not on pressure integration considerations

Three contributions on a submerged structure

- Distributed force \( F_d \)
- Distributed moment \( M_d \)
- Force on free end \( F_{free} \)
- Force on piercing point \( F_{piercing} \)

Standard: 50-yr wave «cut-and-paste» in irregular linear waves

DIMSELO: «Find and replace» highest linear wave with nonlinear SF wave

Use of the Hilbert transfer to calculate the embedment period

**WP2**

Second-order irregular short-crested

- Full second-order short-crested waves
  - Sharma and Dean (1981)
- Standard: not possible without simplifications
- DIMSELO: Full theory implemented
  - 2D FFT calculation in space

**DIMSELO Reference wind turbines**

- Site
  - Dogger Bank
- Water depth
  - $h = 25\text{ m}; h = 35\text{ m}$
- Metocean conditions: Statoil
- Foundations
  1. XL Monopile 25m
  2. XL Monopile 35m
  3. Jacket 35m
  - Designed by Kasper Sandal (DTU)

**Monopile 25m: Soil model**

- P-y soil springs
- Logarithmic decrement of 1st tower bending oscillation
  - $\delta = \frac{2}{\log_{10} \frac{2\pi}{f}}$
- 1.5 % damping as a fraction of critical
  - $\zeta = \frac{\delta}{2\pi} = 0.015$
- Achieved by installing dampers at the mudline

**Monopile 25m**

- Turbine
  - DTU 10MW reference wind turbine
    - $H_{hub} = 119\text{ [m]}$
- DTU controller
- Tower
  - Steel, onshore tower
- Substructure
  - Designed ad-hoc
- Fatigue and Extreme loads
Jacket Model

Monopile 25m
Rotor flapwise with yaw
\[ f = 0.57 \, \text{Hz} \]

Monopile 25m
Tower side-to-side bending
\[ f = 0.23 \, \text{Hz} \]

Monopile 25m
Rotor edgewise bending
\[ f = 0.48 \, \text{Hz} \]

Monopile 25m
Rotor flapwise with tilt
\[ f = 0.59 \, \text{Hz} \]

Monopile 25
Collective flapwise
\[ f = 0.62 \, \text{Hz} \]
MetOcean conditions for DIMSELO structures

- Northern sea location
- Dogger Bank
- Wind speed conditional on $H_s$
- Aligned with waves
- Turbulence
- IEC-61400-1
- $\sum P (H_s, T_p) = 100$

Wind Speed@100 [m] [m/s]            5.8         9.1       13.5     17.6     21.0      23.8

Example: effect of kinematics 1st vs 2nd order

- Histogram
- Sea state
  - $H_s = 3.5 \text{ m}, T_p = 7.5 \text{ m}$
- Mudline x-wise force

Example: effect of kinematics 1st vs 2nd order

- Exceedance probability
- Sea state
  - $H_s = 3.5 \text{ m}, T_p = 7.5 \text{ m}$
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Example: effect of kinematics 1st vs 2nd order

- Time series 30 min
- Sea state
  - $H_s = 3.5 \text{ m}, T_p = 7.5 \text{ m}$
- Mudline x-wise force

A more compact view

- Fatigue IEC-61400-1
- LC 1.6 → operation with NTM
- Simulate N series of 30 minutes
- Extract timeseries of important parameters
  - Mudline Fx [kN]
  - Mudline My[kNm]
  - Blade root Flapwise Mf[kNm]
- DAMAGE EQUIVALENT LOAD (DEL)
  - Regular load that would do the same damage as the irregular one if applied in a 1-min sinusoid

$D \propto \text{DEL}^m$

- $D$ : damage (inverse of lifetime)
- $\text{DEL}$ : damage equivalent load
- $m$ : Wöhler exponent (m=3 for steel)
Morison – 1st order – Long Crested (Base case)

Fatigue due to Mudline Fx

Example: effect of force model

- Histogram
- Sea state
  - $H_s = 3.5$ [m], $T_p = 7.5$ [m]
- Mudline Fx

MacCamy-Fuchs – 1st order – Long crested

Fatigue due to Mudline Fx

Example: effect of force model

- Exceedance probability
- Sea state
  - $H_s = 3.5$ [m], $T_p = 7.5$ [m]
- Mudline Fx

Example: effect of force model

- Time series
- Sea state
  - $H_s = 3.5$ [m], $T_p = 7.5$ [m]
- Mudline Fx

Example: effect of force model

- Power spectral density
- Sea state
  - $H_s = 3.5$ [m], $T_p = 7.5$ [m]
- Mudline Fx
Rainey – 2nd order – Swell
Fatigue due to Mudline Fx

MacCamy-Fuchs – 1st order – Swell
Fatigue due to Blade Root Flapwise moment

Example: effect of force model
- Power spectral density
- Sea state
  - $H_0 = 3.5 \text{ m}, T_p = 7.5 \text{ m}$
- Blade root Flapwise moment

Effect of wave spreading
- Time series
- Sea state
  - $H_0 = 3.5 \text{ m}, T_p = 7.5 \text{ m}$
- Mudline x-wise force
Effect of wave spreading

- Histogram
- Sea state
  - $H_s = 3.5\ [\text{m}], T_p = 7.5\ [\text{m}]$
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Conclusions

- DIMSELO has shed light into effect of improved models on OWT dimensioning loads
- It helped understand when it is useful to adopt a more complex wave force or kinematics model
- For example, on a 25m Monopile fatigue load case:
  - 1st order diffraction made a difference on tower base fatigue
  - the blade loads were insensitive to wave load models
  - 2nd order waves do not significantly influence fatigue loads
- Timeline: Complete the calculations and deliver final report

Effect of wave spreading

- Power spectral density
- Sea state
  - $H_s = 3.5\ [\text{m}], T_p = 7.5\ [\text{m}]$
- Mudline x-wise force

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MacCamy-Fuchs – 1st order – MultiD

Mudline moment $M_y$

Design calculations: today’s practice

- Fatigue calculations
  - Linear irregular waves
  - Morison equation
  - Some critical points
    - Non-linearity in irregular waves
    - Non-linearity in the force model
    - What about wave diffraction of large monopiles?
- Extreme loads
  - Embedment of a 50-yr nonlinear wave in long-crested waves
  - Morison equation
  - Some critical points
    - Directionality in the extreme loads?
    - Non-linearity of the force?
    - Statistical significance of extreme load?
A savings procedure based construction heuristic for the offshore wind cable layout optimization problem

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2018

Supervisors: Prof. Dag Haugland (UiB) and Ahmad Hemmati, PhD.

Deep Wind Conference 2018, Trondheim, Norway

Offshore Wind Cable Layout Optimization

- Offshore wind or inter-array cable layout (OWCL) optimization problem is a NP-hard problem.
- There is similarity between OWCL and capacitated minimum spanning tree (CMST) problem with unit demand which has also been proved to be NP-hard (Papadimitriou, 1978).
- With increasing number of turbine nodes and additional restricted areas in the wind farm, exact methods in solving large instances become inefficient.
- Due to the inefficiencies of the exact methods in solving large instances, heuristics can be used to attain good and feasible solutions.
- Construction, improvement and hybrid heuristics are classical heuristics exploring a limited search space as opposed to large search space in metaheuristics, but using some unique strategies can be used to attain small optimality gap even with classical approaches.

Table of Content

INTRODUCTION

- Offshore Wind Cable Layout (OWCL) Optimization
- Problem Statement and Assumptions
- Constraints: Node crossing/cable crossing, obstacles and out-degree
- Features: Parallel cables and branching
- MILP model used for benchmarking heuristic solutions

HEURISTIC

- Basic idea
- Pseudocode (Esau-Williams)
- Ideas to tackle cable crossing
- Ideas to identify node crossing
- Pseudocode (Obstacle-Aware Esau Williams)

Experimental Results and Modified Algorithm

- Initial results from the Modified Esau-Williams (Wind farms: Walney 1, Walney 2 and Barrow)
- Parameterization and introducing a shape factor
- Improved results
- From construction heuristic to Meta-Heuristic: Future activities (Very large Neighborhood search (VLNS) and GRASP)

Problem Statement and Assumption

Problem:

Input:
1. Location of the turbines and substations
2. Location of the restricted areas and obstacles in the sea bed
3. Cable capacity (maximum power flow or number of turbines allowed on a single cable)

Output: Minimum cable length layout such that there is a unique path from each turbine to one of the substations

Constraints:
1. Cable crossing/Node crossing not allowed
2. Cable capacity must be satisfied
3. Outdegree of each turbine is one (no splitting of power cables)

Assumption:
Cable cost is directly proportional to the length of the cables and does not depend on any other parameter. This is similar to a capacitated minimum spanning tree problem (NP hard) with some additional constraints.
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This is similar to a capacitated minimum spanning tree problem (NP hard) with some additional constraints.

Constraint 1: Cable crossing and Node crossing

The main reasons behind such a constraint are:
1. Need for expensive bridge structure
2. Thermal interference between the two cables results in reducing the cable capacity
3. In case of failure of one of the cable both the cables are affected while repairing

Constraint 2: Power cables cannot be splitted

The out-degree of each turbine node must be one. However, in-degree can be more which is referred to as branching.

Constraint 3: Restricted areas

- Direct links are sometimes not possible due to restricted areas in the sea-bed
- Number of steiner nodes is a design parameter and can be more than the extreme points of the convex hull
- We are making an assumption that any concave and convex restricted area can be represented by a convex hull without compromising on optimality

Allowed: Branching and parallel cables

Both branching and parallel cables provide flexibility to the final layout and may lead to reduction in the total cable length.
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- From construction heuristic to Meta-Heuristic - Future activities (Very large Neighborhood search (VLNS) and GRASP)

Basic idea behind the heuristic

- Esau-Williams’ heuristic is a well-known heuristic for the capacitated minimum spanning tree problem.
- Start with a costly, feasible star layout
- In each iteration remove one link connecting the non-root node with the root node (substation node) resulting in cost saving.

Pseudocode of Esau-Williams’ heuristic

V: set of vertices
A: set of arcs
0: root node
\( c \): cost of the arcs
K: cable capacity
\( R_i \): reduction function value of node i
\( X_i \): connected component containing node i

Final output of the Esau-Williams’ Heuristic

- Capacity = 3

Although CMST and cable layout problems are quite similar but there are additional constraints which are to be satisfied in the offshore wind cable layout problem

Idea to tackle cable crossing

- Non-crossing procedure and Dijkstra are used subsequently to identify shortest feasible path between two nodes \( i_0 \) and \( i_2 \)

Continues until a shortest feasible (non-crossing) path is found between \( i_0 \) and \( i_2 \)

So, the basic idea is that once we have identified the two turbine nodes to be connected using the max reduction function value, we try to use the above idea to find the shortest non-crossing path between them
Obstacle-Aware Esau Williams Heuristic (1/2)

Roblems 1: Obstacle Aware Esau Williams

Data: Grid 4 x 4, Various obstacles
Result: M = obstacles removed spanning [1, 3, 3]

while loop do

while (CurTime > 0) do

for node (i, j) do

| compute K_i | // Reflective value using (4.1.3)
| manifold(i - j) | // equation (2.23)
|
end

for each line segments in L do

| IntersectionArray.add(s) |
end

end

end

L_i = max(|K_i|) // Max value K_i
L_j = max(|K_j|) // Max value K_j

end

While loop #1 continues unless all the reduction values become zero

While loop #2 continues unless the node with highest reduction values gets linked with another node

Obstacle-Aware Esau Williams Heuristic (1/2)

Non-Crossing procedure’s output

Non-Crossing procedure’s output

Challange: Non-Crossing procedure is unable to identify node crossing
Challenge: Non-Crossing procedure is unable to identify node crossing

Solution (1/4): Add new line segments such that node crossings are detected by Non-crossing procedure

Solution (2/4): Add new line segments such that node crossings are detected by Non-crossing procedure

Solution (3/4): Add new line segments such that node crossings are detected by Non-crossing procedure
Solution(4/4): Add new line segments such that node crossings are detected by Non-crossing procedure.

Solution(1/2): Where to add the line segments?

Solution(2/2): Where to add the line segments?
Solution(2/2): Where to add the line segments?

Post joining step

Output from 1st part of the algorithm

Partitioning of turbine nodes in different connected components

Feasible Connection

Assumption: All turbine nodes are in the convex hull of their own connected component and not in the convex hull of others

Experimental Results-2

Experimental Results-3

Experimental Results-1

Experimental Results-3

Walney 1 final layout for K=6

Walney 2 final layout for K=6

Walney 2 final layout for K=6

Experimental Results-3

There is a large optimality gap for Walney 2

The partitioning of the turbine nodes leads to extremely long paths connecting connected components to the substation

For example, the connected component containing nodes 45, 46, 47, 48, 49, 39 is linked with the substation using a long path 45->83->27->51

There is a large optimality gap for Walney 2

The partitioning of the turbine nodes leads to extremely long paths connecting connected components to the substation

For example, the connected component containing nodes 45, 46, 47, 48, 49, 39 is linked with the substation using a long path 45->38->27->51

Existing Model:

- We have compared our results to the optimal solutions attained from an existing MILP model developed by our colleague Arne Klein, UiB, Norway
- The model presented in [Klein and Haugland, 2017] is implemented using CPLEX 12 Python 3.4 API. All the experiments were carried out on a fast computer - Intel Xeon with 72 logical cores and 256GB RAM
- The experiments were carried out for Walney 1, Walney 2, Barrow wind farms and for different cable capacities

Developed Heuristic:

- All the experiments involving the heuristics (Obstacle Aware Esau-Williams) in this work are carried out on a personal computer using 2.5 GHz Intel Core i5 processor and 4GB RAM
- Programming language used is Java and without use of any commercial solver
- The ambition of the first version of the obstacle-aware heuristic is to find good, feasible solutions with less optimality gap [cost(heuristic)/cost(optimal solution)]

Table of Content

- Offshore Wind Cable Layout (OWCL) Optimization
- Problem statement and Assumptions
- Constraints: Node crossing/cable crossing, obstacles and out-degree
- Features: Parallel cables and branching
- MILP model used for benchmarking heuristic solutions

INTRODUCTION

- Basic idea
- Pseudocode (Esau-Williams)
- Ideas to tackle cable crossing
- Ideas to identify node crossing
- Pseudocode (Obstacle-Aware Esau Williams)

EXPERIMENTAL RESULTS

- Initial results from the Modified Esau-Williams (Wind farms: Walney 1, Walney 2 and Barrow)
- Parametrization and introducing a shape factor
- Improved results
- From construction heuristic to Meta-Heuristic: Future activities (Very large Neighborhood search (VLNS) and GRASP)
Ideas/Activities to reduce the opt. gap

- Modifying the reduction function and the algorithm such that radial topologies are encouraged and thus, long paths to the substation are avoided.
- Using a multi-exchange large neighbourhood search for finding the locally optimal solution.

Introducing weight parameter in reduction function

\[
S(t) = (j \in V_0 : j \in N_t, j \notin L_t, |N_t| = 1) \leq K \tag{2.2.11}
\]

\[
f(j) = \begin{cases} 
\min \{ f \in \arg \min_k \mathcal{V}_k(\mathcal{C}_j) + \mathcal{V}_j \} : f \in S(t), W \in \mathbb{W} \end{cases} \tag{2.2.12}
\]

\[
R_j = \left\{ c_{i,j} - \min \{ \mathcal{C}_j \} + \mathcal{V}_j : j \in S(t), S(t) \neq \emptyset \right\} \tag{2.2.13}
\]

As the value of weight parameter W increases, turbine nodes closer to the substation will be preferred.

Results from exact, obstacle aware Esau Williams and algorithm with weight parameter

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Exact</th>
<th>Obstacle-Aware</th>
<th>Parametric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Value</td>
<td>Gap</td>
</tr>
<tr>
<td>Walney 1</td>
<td>41418</td>
<td>43850</td>
<td>1.05</td>
</tr>
<tr>
<td>Barrow</td>
<td>18374</td>
<td>20980</td>
<td>1.14</td>
</tr>
<tr>
<td>Walney 2</td>
<td>52981</td>
<td>63568</td>
<td>1.19</td>
</tr>
</tbody>
</table>

K=5

<table>
<thead>
<tr>
<th>Wind Farm</th>
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<th>Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walney 1</td>
<td>43420</td>
<td>44444</td>
<td>1.0235</td>
<td>43488</td>
</tr>
<tr>
<td>Barrow</td>
<td>20691</td>
<td>21815</td>
<td>1.054</td>
<td>21105</td>
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<td>62730</td>
<td>1.11</td>
<td>57016</td>
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k=4

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<th>Value</th>
<th>Gap</th>
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</thead>
<tbody>
<tr>
<td>Walney 1</td>
<td>47411</td>
<td>49534</td>
<td>1.044</td>
<td>49396</td>
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<tr>
<td>Barrow</td>
<td>232208</td>
<td>23243</td>
<td>1.001</td>
<td>23243</td>
</tr>
<tr>
<td>Walney 2</td>
<td>63496</td>
<td>73574</td>
<td>1.15</td>
<td>63579</td>
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Improved result for Walney 2

Results from exact, obstacle aware Esau Williams and algorithm with weight parameter

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<td>63579</td>
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Change in cable length with weight parameter
Ideas/Activities to reduce the opt. gap

- Modifying the reduction function and the algorithm such that radial topologies are encouraged and thus, long paths to the substation are avoided
- Using a multi-exchange large neighbourhood search for finding the locally optimal solution

Questions?

Thank You!

Project is supported by Hordaland fylkeskommune.
The Challenge

• Wind industry plagued by underperformance, failures, & expenses:
  o Improvements required in wind-farm performance & reliability, together w/ reduced uncertainty & expenditures to achieve cost targets
  o 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.:
  o FLORIS: Steady-state wind-farm performance & controls, but no turbine loads
  o DWM: Both performance & loads, including dynamics, but individual or serial solution limits accuracy & usefulness
  o SOWFA: Large-eddy simulation (LES CFD) computational demand means very few runs

Objective & Approach

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

Wake Planes, Wake Volumes, & Zones of Overlap

FAST.Farm-Generated w/ Stepped Yaw – 8m/s Neutral

Siemens AG, NREL 27821
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)
- Identify parameters that minimize wake-deficit & wake-meandering error between FAST.Farm & SOWFA.

SOWFA-Derived Wake Deficit & Centerline

<table>
<thead>
<tr>
<th>Case</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N</td>
<td>Neutral, 10% TI, 0.2 shear, normal operation</td>
</tr>
<tr>
<td>2</td>
<td>U</td>
<td>8 m/s, unstable, 10% TI, 0.2 shear, normal operation</td>
</tr>
<tr>
<td>3</td>
<td>S</td>
<td>8 m/s, stable, 5% TI, 0.2 shear, normal operation</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>8 m/s, stable, 5% TI, 0.2 shear, normal operation</td>
</tr>
<tr>
<td>5</td>
<td>80%</td>
<td>Neutral, 10% TI, 0.2 shear, operation with yaw steps</td>
</tr>
<tr>
<td>6</td>
<td>N</td>
<td>Neutral, 10% TI, 0.2 shear, operation with yaw steps</td>
</tr>
</tbody>
</table>

Calibration Approach

- FAST.Farm captures overall wake-meandering statistics predicted by SOWFA across different stability conditions, w/ some 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 & boundary layer).
- Comparisons hampered by lack of statistical convergence (30-min/case).

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

Validation Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Number of turbines</th>
<th>Turbine spacing</th>
<th>Mean hub-height wind speed</th>
<th>Atmospheric stability</th>
<th>Turbulence intensity</th>
<th>Shear exponent</th>
<th>Yaw error</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>1</td>
<td>5</td>
<td>Neutral</td>
<td>10%</td>
<td>0.2</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>N0</td>
<td>1</td>
<td>10</td>
<td>Neutral</td>
<td>10%</td>
<td>0.2</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>S0</td>
<td>1</td>
<td>5</td>
<td>Stable</td>
<td>5%</td>
<td>0.2</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>N0</td>
<td>3</td>
<td>8</td>
<td>Neutral</td>
<td>10%</td>
<td>0.3</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>S0</td>
<td>3</td>
<td>8</td>
<td>Stable</td>
<td>5%</td>
<td>0.2</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>U0</td>
<td>3</td>
<td>8</td>
<td>Unstable</td>
<td>10%</td>
<td>0.1</td>
<td>0°</td>
<td></td>
</tr>
</tbody>
</table>

Ongoing Work – Validation of FAST.Farm Against SOWFA

- Currently running SOWFA simulations—w/ modest variations in inflow & control, independent from those used to support calibration—to validate FAST.Farm.
- FAST.Farm calibration parameters are untouched to check their robustness & range of applicability.
- Results will be presented at TORQUE 2018.

Results suggest that FAST.Farm would benefit from:
- Different calibration parameters for different stability conditions or yaw errors.
- Improved physics in the eddy-viscosity formulation.

Calibration Results

- FAST.Farm captures change in wake-deficit evolution w/ downstream distance, but doesn’t fully capture change predicted by SOWFA across different stability conditions or yaw errors.
- Still reviewing, but think SOWFA predicts fast wake recovery in U due to anisotropic turbulence.
- Results suggest that FAST.Farm would benefit from:
  - Different calibration parameters for different stability conditions or yaw errors.
  - Improved physics in the eddy-viscosity formulation.

Next Steps

- Complete initial validation of FAST.Farm.
- Release FAST.Farm as public, open-source software through OpenFAST.
- Apply FAST.Farm by including turbine loads in wind-farm controls design/testing.
- Use FAST.Farm with HFM symbiotically in a multi-fidelity approach to support validation, UQ, & design.
- 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.
- Address FAST.Farm limitations through more development.
Carpe Ventum!

Jason Jonkman, Ph.D.
+1 (303) 384 – 7026
jason.jonkman@nrel.gov
Motivation


Normalized power

\[ \text{Turbine} \sim 35\% \text{ Power drop} \]

Nysted, \( x/D = 10.3 \) (278 ± 2.5°)

Horns Rev, \( x/D = 7.0 \) (270 ± 2.5°)

What can be done to limit wake effects?

Control strategies:
- Yaw control
- Pitch control
- TSR control

Wind farm layout

Turbine design

Model wind turbines

**NTNU**
- \( D = 0.89 \text{m} \)
- NREL S826
- Small hub & tower
- CCW rotation

**Small NTNU**
- \( D = 0.45 \text{m} \)
- NREL S826
- Relative big hub & tower
- CCW rotation

**ForWind**
- \( D = 0.58 \text{m} \)
- SD 7003
- Low blockage
- CW rotation

Collaboration project

Experimental Campaign
- Different rotor designs
- Same wind tunnel
- Single turbine and multiple turbine arrays

Influence of yaw misalignment on the wake development

Collaboration project
Model wind turbines

Streamwise velocity 6D behind +30° yawed turbine

Model wind turbines

Streamwise velocity 6D behind +30° yawed turbine

Experimental setup

**Publications**

"Comparative study on the wake deflection behind yawed wind turbine models"
Published in Journal of Physics: Conf. Series

"Wind tunnel experiments on wind turbine wakes in yaw: Effects of inflow turbulence and shear"
Posted as discussion paper on Wind Energy Science

"Wind tunnel experiments on wind turbine wakes in yaw: Redefining the wake width"
Posted as discussion paper on Wind Energy Science

"Blind test 5 - The wake behind a yawed model wind turbine"
In process

"Performance and loads of two interacting wind turbines operated at different yaw"
In process

"An Experimental Study on the Far Wake Development behind a Yawed Wind Turbine"
Results

Rotor size and turbine dimension have large influence on wake shape.
Wake behind yawed turbine is complex and asymmetric.
Larger wake deflection from line wake analysis.
Analytical wake models over predict wake deflection.

Conclusions

Thank you for the attention!
I’m looking forward to your Questions.
G1) Experimental Testing and Validation

Wind tunnel experiments on wind turbine wakes in yaw: Redefining the wake width, J. Schottler, ForWind, University of Oldenburg

A Detached-Eddy-Simulation study, J. Göing, Technische Universität Berlin

BOHEM (Blade Optical HEalth Monitoring), P. McKeever, ORE Catapult

Scaled Wind Turbine Setup in Turbulent Wind Tunnel, F. Berger, CvO University of Oldenburg
Wind tunnel experiments on wind turbine wakes in yaw: Redefining the wake width

J. Schottler$^1$, J. Bartl$^2$, F. Mühle$^1$, J. Peinke$^{1,4}$, L. Sætran$^2$, M. Hölling$^1$

1 ForWind, Institute of Physics, University of Oldenburg, Germany
2 Norwegian University of Science and Technology (NTNU), Trondheim, Norway
3 Norwegian University of Life Sciences, As, Norway
4 Fraunhofer IWES, Oldenburg, Germany

jannik.schottler@forwind.de

Motivation

Field measurements
• expensive
• limited availability
• uncontrolled boundary conditions

Numerics
• computational costs
• turbulence models
• validation?

Experiments
• inexpensive
• controlled environment
• tunable boundary conditions
• upscaling?

Motivation

Field measurements
• expensive
• limited availability
• uncontrolled boundary conditions

Numerics
• computational costs
• turbulence models
• validation?

Experiments
• inexpensive
• controlled environment
• tunable boundary conditions
• upscaling?
Wakes Experimentally

• turbine models are not standardized
  • varying blade design / geometry / control...

• how sensitive are results to facility/turbine model/...?
  • experiments lack systematics and comparability

Here:

2 turbines, 2 geometries, 2 scales
1 facility/setup

Thorough analyses of wakes
from mean velocity to two-point statistics,
including yaw misalignment

Two-point statistics

<table>
<thead>
<tr>
<th>Time series</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>1.4</td>
</tr>
<tr>
<td>1.6</td>
</tr>
<tr>
<td>1.8</td>
</tr>
</tbody>
</table>

© ForWind

Neunaber, ForWind
60 cm

Schottler, ForWind
58 cm

Medici, KTH Mechanics
25 cm

Campagnolo, Politec Milano
2 m
Two-point statistics

Increment PDF

\[ \lambda^2(\tau) = 0 \]

\[ \lambda^2 = 0.01 \]

\[ \lambda^2 = 0.2 \]

[Chillà 1996]

\[ F(\tau) = \frac{\langle (\tau - \langle \tau \rangle)^4 \rangle}{\langle \tau^2 \rangle^2} \]

Quantify incr. PDFs shape:

\[ \lambda^2(\tau) = \frac{\ln(F(\tau)/3)}{4} \]

with

\[ \lambda^2 = 0 \]

\[ \lambda^2 = 0.01 \]

\[ \lambda^2 = 0.2 \]

[Chillà 1996]

\[ F(\tau) = \frac{\langle (\tau - \langle \tau \rangle)^4 \rangle}{\langle \tau^2 \rangle^2} \]

Quantify incr. PDFs shape:

\[ \lambda^2(\tau) = \frac{\ln(F(\tau)/3)}{4} \]

velocity increment

\[ u_\tau = \langle \tau \rangle - \langle \tau \rangle \]

increment PDF

velocity increment

\[ u_\tau = \langle \tau \rangle - \langle \tau \rangle \]

velocity increment

\[ u_\tau = \langle \tau \rangle - \langle \tau \rangle \]

velocity increment

\[ u_\tau = \langle \tau \rangle - \langle \tau \rangle \]
Two-point statistics

Velocity increment
\[ u_\tau = u(t + \tau) - u(t) \]

Increment PDF

Quantify incr. PDFs shape:
\[ \chi^2(x) = \frac{\text{ln}(F(u_\tau))}{3} \]

\[ \chi^2 = 0.01 \]
\[ \chi^2 = 0.5 \]

\[ \lambda^2(\tau) = \text{ln}(F(u_\tau)/3)^{4/3} \]

Setup & Overview

Full plane, Laser Doppler Anemometer measurements

The non-yawed wakes

\[ \langle h/\text{Re}_D \rangle \]

\[ \langle \text{TKE} \rangle \]

\[ \langle h/\text{Re}_D \rangle \]

\[ \langle \text{TKE} \rangle \]

\[ \langle h/\text{Re}_D \rangle \]

\[ \langle \text{TKE} \rangle \]
The non-yawed wakes

Shape parameter $\lambda^2(\tau)$

Radial wake areas

Different radial areas of interest!
Radial wake areas

So far:

- circular wake shape
- intermittent flow regions surrounding the velocity deficit
- increased wake width
- qualitatively comparable results for both turbines
So far:
- circular wake shape
- intermittent flow regions surrounding the velocity deficit
- increased wake width
- qualitatively comparable results for both turbines

Yaw misalignment:
\[ \gamma = \pm 30^\circ \]
Yaw misalignment \( y/D \)

- lateral deflection
- curled shape
- vertical transport
- depends on rotational direction!

Curled Wake in yaw - towards quantification

- polynomial fit
- minimum

\[ y/D \]

\[ z/D \]
Curled Wake in yaw - towards quantification

- 'curl' observed for all wakes
- τ tilt in opposite direction
- different direction of rotation!
- interaction with the ground/tower shadow

\[ \gamma = \pm 30^\circ \]

in accordance with [Bastankhah & Porté-Agel 2016]

Parameter comparison at \( \gamma = -30^\circ \)

- lateral deflection
- curled shape
- vertical transport

\[ \frac{\omega}{\nu_{	ext{ref}}} \]
Parameter comparison at $\gamma = -30^\circ$

- lateral deflection
- curled shape
- vertical transport
- similar shape as <u>
- pronounced outer ring (turbine specific)
- distinct ring surrounding TKE
- broader wake area
- not included in models

Summary & conclusion

- wake measurements with focus on yaw misalignment
  - full plane LDA data
  - 2 model wind turbines, differing in size/design
  - 3 yaw angles, 3 inflow conditions
  - > 20 wakes total
Summary & conclusion

- wake measurements with focus on yaw misalignment
  - full plane LDA data
  - 2 model wind turbines, differing in size/design
  - 3 yaw angles, 3 inflow conditions
  - > 20 wakes total

- wake analysis including two-point statistics
  - radial wake extension significantly larger when including two-point statistics!
  - important for downstream turbine loads
    -> affecting wake steering application and wind farm layout

- Blind test 5 coming up
- data available for cooperation/validation

Curl parametrization

- 'curl' observed for all wakes where \( \gamma \pm 30^\circ \)
- further deflection of 'ForWind'-wake
- tilt in opposite direction
- interaction with the ground/tower shadow

in accordance with [Bastankhah & Porté-Agel 2016]
Shape parameter $\lambda^2(\tau)$

Wake center detection

Wake center detection

Wake center detection

Wake center detection

$\text{For } -D/2 \leq z \leq D/2$

$P^\ast = \sum_{i=1}^{10} \rho A_i \langle u_i(t) \rangle_{A_i}^3$

$\langle u_1(t) \rangle_{A_1}^3, \langle u_2(t) \rangle_{A_2}^3, \langle u_i(t) \rangle_{A_i}^3$...
Wake center detection

<table>
<thead>
<tr>
<th>Turbine</th>
<th>( \gamma )</th>
<th>Wake center</th>
<th>Bird angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTNU</td>
<td>(-30^\circ)</td>
<td>(-0.32)</td>
<td>(-3.0^\circ)</td>
</tr>
<tr>
<td>ForWind</td>
<td>(-30^\circ)</td>
<td>(-0.36)</td>
<td>(-3.6^\circ)</td>
</tr>
</tbody>
</table>

Curled wake in yaw - a general effect?

[Howland et al. 2016]
Curled wake in yaw - a general effect!

[Bastankhah & Porté-Agel 2016]

Curled wake observed for drag disc (30mm) model wind turbines (150mm, 580mm, 890mm)

[Bastankhah & Porté-Agel 2016]
A Detached-Eddy-Simulation study

Proper-Orthogonal-Decomposition of the wake flow behind a model wind turbine

J. Göing, J. Bartl, F. Mühle, L. Sætran, P.U. Thamsen
Technical University of Berlin, Norwegian University of Science and Technology, Norwegian University of Life Sciences

Introducing the UT2 (Circulating tank 2) at the TU Berlin

- Drive: 2 motors, 1.6 MW each
- Pump: Q = 60000 l/s at H = 2 m
- Flow speed up to 9 m/s
- One of the biggest circulating water tanks worldwide
- Built in 70's and recently renovated
- Suitable for studies of ship properties as well as of floating wind turbine models

Methods

LDA-Experiment conditions

(a) Test wind turbine

(b) Tip speed ratio

Simulation conditions

(a) CFD – test area

(b) Sliding mesh and grid size

Motivation

Real problem in the wind park optimization?

Detached-Eddy-Simulation (DES)

CFD Methods
- RANS
- LES

Simulation properties
- Mean values
- Large eddies
Proper-Orthogonal-Decomposition (POD)

\[ S = U \cdot \Sigma \cdot V^T \]

Operating points in the wake flow

\[ x/D: 1 \quad 3 \quad 6 \]

POD of the flow field in x/D=1

\[ \bar{u} = u/u_{ref} \]

Normalized coherent streamwise velocity \( \bar{u} = \bar{u}/u_{ref} \) (coherent motions)
Results

Fluctuation loads (significant frequencies)

![Graph showing fluctuation loads](image)

**Note:**

1p: Interaction between the rotation frequency of one blade and the tower.

Validation of the frequency

![Graph showing validation of frequencies](image)

References:


Conclusion

1. DES and POD
   a. Velocity components, turbulence kinetic energy
   b. Coherent motions (tip vortex, root vortex)
   c. Fluctuation load (1p frequency)

2. Future studies
   a. Different inflow/boundary conditions
   b. Wake flow analyses for more than one turbine
   c. Optimization of the wind park planning

Thank you for your attention...

...Questions?
BOHEM – Blade Optical Health Monitoring

18/01/2018  |  Paul McKeever

Agenda

• Project partners
• Project objectives
• How BOHEM works
• BOHEM initial results
• Latest BOHEM results
• Summary

WideBlue Ltd is multi-disciplinary product design and product development consultancy based in Glasgow. WideBlue’s team of product, mechanical, electronic and software engineers, physicists and optical designers have years of experience of taking products from design through to successful manufacture and commercialisation.

The Offshore Renewable Energy Catapult is the UK’s flagship technology innovation and research centre for advancing wind, wave and tidal energy. ORE Catapult participates in large-scale collaborative R&D and innovative commercial and public funded projects, amassing vast technical knowledge and know-how.

ORE Catapult

Our Vision:
Abundant, affordable energy from offshore wind, wave and tide

• Reduce the cost of offshore renewable energy
• Deliver UK economic benefit
• Engineering and research experts with deep sector knowledge
• Independent and trusted partner
• Work with industry and academia to commercialise new technologies

80+ technical experts

Blade Cross-Sectional Deformation

• The current generation of large wind turbines have blades in excess of 80m long, with a typical chord length of 6m
• This means that there are extremely large unsupported panels around the max chord region of the blade which can deform out of plane when the blade bends
• These deformations stress the panels in the transverse direction (potentially causing delamination and create peeling stresses at the trailing edge bond line)

In addition to this phenomenon of panel deformation, the whole blade cross-section can shear as a result of combined torsional and shear loading, which generates stresses at the bond between the shear webs and the spar cap or the blade shell, depending on blade architecture.

• The use of large flatback aerofoils further compounds this issue.
Blade Cross-Sectional Deformation (Flap Max)

Nonlinear and linear deflections are in opposite directions!

Blade Cross-Sectional Deformation (Edge Min)

Nonlinear deflections are much larger than linear

Bohem Concept

BOHEM's robust root mounted vision system tracks the displacement of a series of reflective markers installed in the blade’s most critical areas. The reflective markers are passive, low cost, easy to install and can be removed without damage to the blade.

BOHEM Process

- Illuminate markers and acquire image in reference state
- Isolate markers in reference image
- Isolate markers in each frame
- Remove global translation and rotation to map each section to reference state for each frame, then display scaled deformation
- Compare to finite element model

Blade Cross-Sectional Deformation

- It is clear that, whilst blades are beam like structures, their hollow structure means that the cross section can deform and the assumption of ‘plane sections remaining plane’ cannot be used. The structural designer must use nonlinear shell or brick based 3D FE (finite element) models to characterize how panels deform, and these models must be validated.
- ORE Catapult and Wideblue Ltd have developed the BOHEM system to monitor blade cross-sectional deformation

Raw Footage

Reflectors 5m - 20m in a 40m Blade
Footage Processing

BOHEM Validation

- BOHEM can be used as a ‘virtual stringpot’ to measure the displacement between two points
- It has been validated against stringpot measurements during static blade testing
- Unfortunately, the stringpot measurements were not reliable so in the final test laser measurement mounted on telescopic poles was used
- Overall, good agreement was achieved but it is hard to say whether measurement inaccuracy is responsible for discrepancies...
- A lot of lessons have been learnt for next time!

<table>
<thead>
<tr>
<th>Measurement Location</th>
<th>BOHEM Prediction (mm)</th>
<th>FE Prediction (mm)</th>
<th>Test Value Stringpot (mm)</th>
<th>Test Value Laser (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1 Leading edge</td>
<td>100%</td>
<td>108%</td>
<td>81%</td>
<td></td>
</tr>
<tr>
<td>Test 1 Trailing edge</td>
<td>100%</td>
<td>104%</td>
<td>91%</td>
<td></td>
</tr>
<tr>
<td>Test 2 Leading edge</td>
<td>100%</td>
<td>108%</td>
<td>91%</td>
<td></td>
</tr>
<tr>
<td>Test 2 Trailing edge</td>
<td>100%</td>
<td>108%</td>
<td>91%</td>
<td></td>
</tr>
<tr>
<td>Test 3 Leading edge</td>
<td>100%</td>
<td>87%</td>
<td>71%</td>
<td>103%</td>
</tr>
<tr>
<td>Test 3 Trailing edge</td>
<td>100%</td>
<td>254%</td>
<td>181%</td>
<td>181%</td>
</tr>
</tbody>
</table>

Post Processing

Summary and Further Work

- BOHEM is a novel method of monitoring cross-sectional deformation based on acquiring images of reflective markers
- It has been proven to give useful results during full scale blade tests
- The long term goal of the BOHEM project is to develop a low cost health monitoring mechanism for blades in service
- By tracking the deflection envelope and how it changes over time for a given wind speed (known from SCADA data) BOHEM could act as an early warning system for panel delamination or trailing edge debonding

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Scaled wind turbine setup in turbulent wind tunnel
MoWiTO 1.8 (Model Wind Turbine Oldenburg 1.8 m)
Frederik Berger, Lars Kröger, David Onnen, Vlaho Petrović and Martin Kühn
ForWind – Carl von Ossietzky University Oldenburg
Trondheim – EERA DeepWind conference
January 18, 2017

Motivation
• Interaction of turbulent wind w/ wind turbine in controlled wind tunnel environment:
  • Loads
  • Aerodynamics
  • Control
• Scaling objectives:
  1. Representative aerodynamic response in turbulence
  2. Realistic characteristic curves
  3. Characteristics Re insensitive

Scaling: Aerodynamics
Exchange of airfoils

Blade design
• Carbon fiber with foam spar
• Composite blade weight ~160 g
• Glued on metal inlet
• Flapwise strain gauge
• Pitch motor housing
• Pitch bearing shaft surface
• First eigenfrequency ~39 Hz

Scaling: Global Parameters
Parameters
• Based on NREL 5MW
• Keep design TSR (~7.5)
• Scaling parameters:
  • Length scaling
    \[ \frac{L_{\text{scaled}}}{L_{\text{reference}}} = \frac{1.8 \text{ m}}{12 \text{ m}} = 0.15 \]
  • Time scaling
    \[ \frac{\Omega_{\text{scaled}}}{\Omega_{\text{reference}}} = \frac{600 \text{ rpm}}{12.1 \text{ rpm}} = 49.6 \]

Rated values Scaling factor Reference Scaled
Revolutions \( n_1 \) \( n_2 \) 12.1 rpm 600 rpm
Power \( n_{1u} \) \( n_{1v} \) 5 MW 363 W
Wind speed \( n_{2u} \) \( n_{2v} \) 11.4 m/s 8.1 m/s

Reynolds number \( n_{1u}^2 * n_{2u} \sim 10^7 \sim 10^8 \)

Objective 1: Aerodynamic response in turbulence

Results

TurbSim wind file
NREL 5 MW Scaled turbine
Scaled wind++
downscaling
downscaling
FAST Sim at 7 rpm
FAST Sim at 490 rpm

SMW FAST Scal. FAST

Mio (MW)
Turbine key facts

- Sensors and actuators:
  - Strain gauges at blade root (flapwise)
  - Strain gauges at tower base (fore-aft, side-side)
  - Torque meter with encoder
  - Individual pitch motors
  - Real time control and data acquisition
- Operation:
  - 400 - 600 rpm
  - Rated wind 8.1 m/s

Active Grid

- 20 split axes with flaps in each, horizontal and vertical, direction
- 80 servomotors driving the axes
- Reproduce turbulent wind patterns, e.g. based on free field measurements

Nacelle layout

Aerodynamic characterisation in wind tunnel

Wind Tunnel at University Oldenburg

- WindLab; Dimensions (H x W x L) 3 x 3 x 30 m³
- Open test section or closed test section
- \( V_{wind} \) up to 42 m/s (closed) or 30 m/s (open)

Objective 2: \( C_p \) and \( C_t \) characteristic

- Slope matches
- Offset due to difference in glide ratio of profiles
- Good match
- Error bars indicate influence of \( \pm 0.1 \) m/s in reference wind
Objective 3: Influence of Reynolds number

Summary

- Introduction of test setup:
  - Model wind turbine (D=1.8 m)
  - Fully equipped with sensors
  - Blade aerodynamics and loads scalable to NREL 5 MW turbine
  - Wind tunnel with active turbulence grid
  - Reproduceable turbulent patterns

- Planned experiments:
  - Engineering models (e.g. dyn. inflow)
  - Turbulent inflow (temporal/spatial)
  - PIV investigations
  - Controller testing

Experiments: Turbulent Inflow

Acknowledgements

This work was partially funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) in the Smart Blades 2.0 project (0324032D) and the state of Lower Saxony (ZN3092).

- Turbulent protocol based on free field measurement
- Mean wind velocity 5.7 m/s
- Turbulence intensity 10.4 %
G2) Experimental Testing and Validation

Documentation, Verification and Validation of Real-Time Hybrid Model tests for the 10MW OO-Star Wind Floater semi FOWT, M.Thys, SINTEF Ocean

Validation of the real-time-response ProCap measurement system for full field flow measurements in a model-scale wind turbine wake, J.Bartl, NTNU

Experimental Study on Slamming Load by Simplified Substructure, Byoungcheon Seo, University of Ulsan, Korea

Physical model testing of the TetraSpar floater in two configurations, M.Borg, DTU Wind Energy
DOCUMENTATION VERIFICATION AND VALIDATION OF REAL-TIME HYBRID MODEL TESTS WITH THE 10MW OO-STAR WIND FLOATER

Maxime Thys (SINTEF Ocean)
Lene Eliassen (SINTEF Ocean)
Petter A. Berthelsen (SINTEF Ocean)
Valentin Chabaud (SINTEF Ocean)
Thomas Sauder (AMOS/NTNU)

Layout

- Model testing: motivation and limitations
- Real-Time Hybrid Model testing
- OO-Star Wind Floater ReaTHM tests
- Verification
- Conclusion

Motivation for model tests

- Common to all offshore structures
- Significant investments should be de-risked and optimized
- Some physical effects are not modelled correctly by engineering tools yet
- Some physical effects are not known yet
- Specific to FOWT
- Complex coupling between wind and wave loads, structure and blade dynamics.
  → Issue: the experiments must capture these couplings correctly

Limitations of classical approaches

- Tests in wave tanks, using fans to generate the aerodynamic loading
  - Challenge 1: ensure a correct wind field above the wave field → accuracy, repeatability, traceability
  - Challenge 2: ensure a correct mass distribution of the RNA model
  - Challenge 3: Froude/Reynolds scaling conflict, and rotor re-design by “Performance scaling”

Real-Time Hybrid Model (ReaTHM®) testing

- Measured platform motions
- Actuated rotor loads
- Waves & current
- Wind
- Aeroelastic simulation (NREL’s FAST code)
- Model testing (Ocean Basin)

Strong points of ReaTHM® testing?

- Realistic and controlled rotor loads
- Possibility to test extreme conditions
- Cost-effective and flexible

Any challenges?

- Multidisciplinary
- Physical laboratory
- Control systems
- Numerical laboratory

How to ensure high quality testing?
Lifes50+ H2020 project (http://lifes50plus.eu/)
OO-Star Wind Floater with DTU 10MW turbine
Tested in Nov 2017 in the Ocean Basin at SINTEF Ocean
Scale 1/36
Environmental conditions of Gulf of Main (depth 130m)

Objectives:
- Concept performance verification
- Data for num. calibration
- Develop hybrid methods

Verification: Stepwise approach
- General: Sensitivity study
- Substructure Verification
- Verification of complete system

Verification of Physical Substructure
- Pullout
- Decay
- Repetitions

Verification: Sensitivity study
- How important are each of the turbine load components for operational and parked conditions?
- Realized by use of Riflex-SIMO-Aerodyn, where
- rotor loads are modified one by one.
- Sensitivity to:
  - aerodynamic sway, heave, pitch, and yaw
  - Gyro moments/centrifugal forces
  - Vertical and horizontal directionality
- 16 loading conditions

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>EC1</th>
<th>EC2</th>
<th>EC3</th>
<th>EC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>m/s</td>
<td>8.6</td>
<td>11.4</td>
<td>20.9</td>
<td>44.0</td>
</tr>
<tr>
<td>Ti</td>
<td>%</td>
<td>12.7</td>
<td>13.4</td>
<td>9.8</td>
<td>11.0</td>
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<tr>
<td>Wind model</td>
<td></td>
<td>NTM</td>
<td>NTM</td>
<td>NTM</td>
<td>NTM (EOM)</td>
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<tr>
<td>Power loss corr.</td>
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<td>0.11</td>
<td>0.14</td>
<td>0.16</td>
<td>0.11</td>
</tr>
<tr>
<td>M</td>
<td>m</td>
<td>2.3</td>
<td>2.5</td>
<td>3.6</td>
<td>10.0</td>
</tr>
<tr>
<td>T</td>
<td>m</td>
<td>0.7</td>
<td>0.5</td>
<td>0.9</td>
<td>10.0</td>
</tr>
<tr>
<td>Wave spectrum</td>
<td></td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
</tr>
</tbody>
</table>

Verification: Sensitivity study
- Influence on standard deviation for quantities of interest (DOF1-6, mooring line tensions, BM and SF)

- Aerodynamic sway small
- 15% tension and 8% yaw and pitch
- Aerodynamic heave small
- 12% tension
- Aerodynamic pitch (18% pitch and 10% SF): 12% pitch and x12% BM
- Aerodynamic yaw (85% on yaw (small)): small
- Vertical directionality small
- 7% pitch and 15% tension

=> 6 actuators in two parallel horizontal planes to apply all loads except heave
Verification of Numerical Substructure

Physical part of the experiments emulated in SIMA for verification of:
- Allocation (rotor loads->forces on actuators 1-6)
- Scaling
- Applied actuators forces

Verification of Control System

Main objectives:
- Reference tracking
- Disturbance rejection

Through:
- Chirp tests
- Following tests

Verification of Complete System: Decay

Pitch decay test without ReaTHM system and with the system in following mode

Verification of Complete System: Repetition

Test repetition:
- DLC 1.6
- Waves: Pierson-Moskowitz Hs=7.7m and Tp=12.4s
- Wind: NTM 8m/s

Conclusions

- ReaTHM® testing is a multidisciplinary method
- Sensitivity analysis is key in the design process
- New verification and documentation methods developed for substructures and complete system
- Examples shown from Life50+ with OO-Star Wind Floater
- More work needed to address experimental uncertainty of hybrid tests -> Phase 2 of Life50+ in March 2018 (Nautilus-DTU10)
Acknowledgments

Also, we are grateful to Dr. techn. Olav Olsen AS for the permission and contribution to set up the public 10MW semi-submersible design based on their concept of the OO-Star Wind Floater (www.olavolsen.no).
Validation of the real-time-response ProCap system for full field wake scans behind a yawed model wind turbine

Jan Bartl1, Andreas Müller2, Andrin Landolt3, Franz Mühle4, Mari Vatn1, Luca Oggiano1,5, Lars Saetran1

EERA DeepWind2018, January 17-19, 2018, Trondheim, Norway

Wake model validation across the scales

Full-scale measurements

Wind tunnel experiments

Simulations

- Pressure measurements (Pitot tube)
- Hot-wire measurements
- Laser-Doppler measurements (LDA)
  - Traverse of single grid points
  - Interpolation in post-processing
  - Measurement time full wake (2m x 1m) ≈ 5 hours

Flow field measurements
- Particle Image Velocimetry (PIV)
- Limited measurement window

Experimental setup ProCap

- Developed at ETH Zürich and its spin-off streamwise

The ProCap system consists of:
  - a hand-guided 5-hole pressure probe equipped with three markers
  - a motion capture camera system
  - a real-time data processing and visualization system

Turbine interaction & Wake flow prediction

ProCap: Experimental setup
Real-time response data acquisition

Comparison of results: \( \text{u and v at } x/D = 3, \gamma = 30^\circ \)

Comparison of results: \( \text{u and v at } x/D = 9, \gamma = 30^\circ \)

Conclusions
- Successfully validation of ProCap measurement system for multiple wake scans
- Precise capture of strong velocity gradients and flow circulation
- Significantly shorter recording time
  \( t_{\text{ProCap}} = 10 \text{ min} \) vs \( t_{\text{LDA}} = 6 \text{ h} \).
- Real-time data acquisition
  + Review and discussion of the results during measurement

\[ \Rightarrow \text{Fast & accurate system for wind turbine wake measurements} \]

Thank you for your attention.
Introduction

Area: 95,528m², 109th in the world
Population: 51,778,544 people, 27th in the world
(CIA, The World Factbook)

Source: Video Bent-Tommy Larsen Statoil
Source: www.fotoarkivet.no

Source: ABC News.com
• 30 Dec 2015
• Windows and Structures in upper hull failed due to horizontal Slamming
• Wave Height: 16.38 m
• Dead: 1 person
• Injury: 4 people

Source: Petroleum Safety Authority (PSA) 2016
Introduction

- Test model in wide tank, UOU -
- Freeboard: 6 m (full scale), 150 mm (model scale)
- Condition: Irregular wave, sea state 6 (extreme)

Experimental System (UOU Slamming Tank)

Test model (UOU Trimming Tank)

Test Model (Production process at UOU Trimming Tank)

Experimental System (UOU Trimming Tank)

- Trimming Tank
  - Width = 2,170 mm
  - Water depth = 1,000 mm
  - Max. drop height = 1,000 mm
Test model (UOU Slamming Tank)

<table>
<thead>
<tr>
<th>Model</th>
<th>Steel / Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom plate thickness [mm]</td>
<td>3, 5, 8, 10</td>
</tr>
<tr>
<td>Height [mm]</td>
<td>300</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>2,000</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>1,200</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>820</td>
</tr>
<tr>
<td>Dead-rise angle [deg.]</td>
<td>0, 10</td>
</tr>
</tbody>
</table>

Measurement

Comparison between Strain type and Piezoelectric type sensor

Comparison sampling rate

Test model (UOU Slamming Tank)

<table>
<thead>
<tr>
<th>Model</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom plate thickness [mm]</td>
<td>8</td>
</tr>
<tr>
<td>Height [mm]</td>
<td>300</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>2,000</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>1,200</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>820</td>
</tr>
<tr>
<td>Dead-rise angle [deg.]</td>
<td>Cylindrical</td>
</tr>
</tbody>
</table>

Measurement

Comparison between Strain type and Piezoelectric type sensor

Comparison sampling rate

Free wet drop test (UOU Trimming Tank)

Dead-rise angle 0°

Dead-rise angle 10°

Measurement (Sensor location)

<table>
<thead>
<tr>
<th>UOU Trimming Tank Model</th>
<th>UOU Slamming Tank Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead-rise angle 0°</td>
<td>Cylindrical shape</td>
</tr>
<tr>
<td>Dead-rise angle 10°</td>
<td>Dead-rise angle 0°</td>
</tr>
<tr>
<td>Dead-rise angle 3°</td>
<td>Dead-rise angle 10°</td>
</tr>
</tbody>
</table>

0° - 500mm Free drop test (UOU Trimming Tank)

3T

4T

5T

Wood
3° - 500mm Free drop test (UOU Trimming Tank)

10° - 500mm Free drop test (UOU Trimming Tank)

Free wet drop test (Wood & Steel 0° in UOU Slamming Tank)

Experimental Results - 3T_0°

Experimental Results - 5T_0°

Experimental Results - 8T_0°
Free wet drop test (Wood & Steel 0° in UOU Slamming Tank)

- Wood - Dead-rise angle 10°, Drop height : 1m
- Steel - Dead-rise angle 10°, Drop height : 1m
- Steel - Dead-rise angle 10°, Drop height : 1.7m

Experimental Results - 3T_10°

- Max. Deflection : 40mm
- Max. Strain : 0.0007
- Max. Pressure : 0.18MPa

Experimental Results - 5T_10°

- Max. Deflection : 4mm
- Max. Strain : 0.0003
- Max. Pressure : 0.27MPa

Experimental Results - 8T_10°

- Max. Deflection : 2mm
- Max. Strain : 0.0012
- Max. Pressure : 0.29MPa

Experimental Results - 8T_10°_Damped Wave

- Max. Deflection : 4mm
- Max. Strain : 0.0005
- Max. Pressure : 0.45MPa

Experimental Results - 8T_10°_Pressure and Strain (Damped Wave)
Experimental Results (Wood)

**Free wet drop test** (Steel Cylindrical shape in UOU Slamming Tank)

1. Finite element modelling of tested models
   - Using shell elements
   - Mesh / plate thickness ~1.88
   - Fully fixed at upper supporting frame

2. Simplified impulsive pressure shape: Triangular shape
   - Three presentative parameters:
     - Peak pressure
     - Rising time
     - Decaying time

3. Material property definition
   - Strain hardening: Use tensile test data
   - Strain rate hardening: Cowper-Symonds Eq. \( D=40.4 & q=5 \)

\[
\sigma_{eq} = \sigma_0 \left( 1 + \frac{\dot{\varepsilon}}{D} \right)^q
\]

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Yield stress</th>
<th>Ultimate strength</th>
<th>Ultimate strain</th>
</tr>
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<tr>
<td>8</td>
<td>784</td>
<td>433.2</td>
<td>0.2251</td>
</tr>
</tbody>
</table>
Numerical analysis results

4. Deflection: SU-10-8T-1.7m

Discussions & Future work

1. The slamming load characteristics were investigated through experiments with numerical analysis.
2. In case of dead-rise angle 0°, the slamming pressure value is smaller than dead-rise angles 3° and 10° due to the air effect.
3. Air effect comes from the elastic effect, so the model size is made bigger that can be applied to the actual design.
4. The same air effect occurred at dead-rise angle 0°.
5. Pressure increase is directly proportional to the increase of drop height, weight and thickness.
6. It was confirmed that several peak pressures were generated in one drop at dead-rise angle 10° and cylindrical shape models.
7. The largest slamming pressure was observed in the cylindrical shape model.
8. Considering the slamming load in the elastic region, it was taken into consideration that several slamming loads are applied to a single wave load rather than a single pressure value.
9. Further study is necessary to improve its accuracy and reliability, and additional experiments under the same test conditions are required for the uncertainty.
The TetraSpar concept

- Concept developed by Stiesdal Offshore Technologies
- Rationale:
  - Mindset
    - Conventional thinking
    - We have designed this structure – now, how do we build it?
  - TetraSpar thinking
    - Why need to manufacture this way – can we use a design kit?

Introduction

- Scientific ambitions
  - Improving SoE wind-wave testing
  - Detailed hydrodynamic testing
  - Fault & transient conditions

- Tech. development ambitions
  - Proof-of-concept
  - De-risk concept

Experimental setup:
- wave basin
  - DHI deep-water wave basin with 4 x 4 m² wind generator
### Experimental setup: wind turbine model

- DTU 1MW RWT 1:60 scale model from previous campaigns [1-3]
- Match steady thrust curve – 75% increased chord
- Collective blade pitch control
- New rotor design
  - Match (C_L) thr – 30% increased chord
  - Damp thrust mismatch
  - Improve aerodynamic damping

### Experimental program – selected results

<table>
<thead>
<tr>
<th>Test matrix</th>
<th>Environmental conditions</th>
<th>Velocity (m/s)</th>
<th>V ampl 1/3</th>
<th>V ampl 1/2</th>
<th>V ampl 1/2</th>
<th>V ampl 1/2</th>
<th>V ampl 1/2</th>
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</thead>
<tbody>
<tr>
<td>Test matrix</td>
<td>Environmental conditions</td>
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<td>V ampl 1/3</td>
<td>V ampl 1/2</td>
<td>V ampl 1/2</td>
<td>V ampl 1/2</td>
<td>V ampl 1/2</td>
</tr>
</tbody>
</table>

### Results – system damping

- Identification of system damping – free decay tests in 6 DOF, 10 repetitions
- Roll example:

### Experimental program

<table>
<thead>
<tr>
<th>Test matrix</th>
<th>Environmental conditions</th>
<th>Velocity (m/s)</th>
<th>V ampl 1/3</th>
<th>V ampl 1/2</th>
<th>V ampl 1/2</th>
<th>V ampl 1/2</th>
<th>V ampl 1/2</th>
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<tbody>
<tr>
<td>Test matrix</td>
<td>Environmental conditions</td>
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<td>V ampl 1/2</td>
<td>V ampl 1/2</td>
<td>V ampl 1/2</td>
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</table>
Results
ULS waves only
Motion response

Results
ULS waves only
Acceleration response

Results
ULS waves only
Counterweight line tensions
Results

ULS waves only

Counterweight line tensions

Conclusions

• Testing of TetraSpar in semi and spar configurations
• Nonlinear system damping
• Significant subharmonic wave forcing
• C/W tensions dominated by inertia loads
• WT operation observed to reduce max acceleration

References

[1] Borg, T. Kim, N. F. Heilskov, H. Bredmose, Experimental and numerical

campaign: Model tests of a 10 MW floating wind turbine with waves, wind


Counterweight line tensions

Focused wave group – EC11 – H = 0.33m (19.5m)

Spar response
H) Wind farm control systems

Real-time wind field estimation & model calibration using SCADA data in pursuit of closed-loop wind farm control, B.Doekemeijer, Delft University of Technology

Mitigating Turbine Mechanical Loads Using Engineering Model Predictive Wind Farm Controller, J.Kazda, DTU Wind Energy

Local stability and linear dynamics of a wind power plant, K.Merz, SINTEF Energi

Wind farm control, Prof William Leithead, Strathclyde University
Closed-loop control of wind farms
Real-time wind field estimation & model calibration using SCADA data

January 19th, 2018

INTRODUCTION

Introduction
The problem in wind farms: wake interaction

The Horns Rev offshore wind farm (Vattenfall) under foggy conditions. Photograph by C. Steiness, February 2008

Introduction
Axial induction control for wind farms

The Horns Rev offshore wind farm (Vattenfall) under foggy conditions. Photograph by C. Steiness, February 2008

Introduction
Wake redirection control in wind farms

The Horns Rev offshore wind farm (Vattenfall) under foggy conditions. Photograph by C. Steiness, February 2008
Introduction
Wake redirection control in wind farms.

Increased power production
Increased turbine lifetimes
Integration with the electricity grid

Introduction
Wind farm control: current practice in existing farms

Greedy control

Introduction
Wind farm control: bleeding edge – closed-loop wind farm control

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 727477

Introduction
Wind farm control: state of the art – open-loop wind farm control

OUR RESEARCH
Our research

An estimator for a dynamic surrogate wind farm model

WindFarmObserver: State estimation for a dynamic wind farm model

WindFarmSimulator (WFSim)

2. WFSim is publically available on Github: https://github.com/TUDelft-DataDrivenControl/WFSim

• 3D LES model simplified to 2D (assumption of axisymmetry)
• Nonlinear, medium-fidelity dynamical wind farm model
• Mixing length turbulence model with spatial variations
• Validated to high-fidelity LES data in 2-turbine and 3 x 3-turbine case

Results

Calibration of 2D flow field, $T_{\text{in}}$ and $U_\text{in}$

• WFSim meshed at approx. 12000 states
• WFSim initialized with poor $T_{\text{in}}$ and $U_\text{in}$
• Measurements exclusively SCADA data
• Reality modelled by LES with ALM rotor models
• Extremely low computational cost
• Accuracy comparable to the best in the literature (UKF)
CONCLUSIONS

Conclusions

- Real-time calibration of a dynamic wind farm model
  - Freestream wind speed and turbulence intensity
  - Modeling errors within the wind farm
- High accuracy at very low computational cost
  - Comparable accuracy to the Unscented Kalman filter
  - Two orders of magnitude lower computational cost
- Using only SCADA data
- Ongoing work: optimization using the calibrated model
Mitigating Turbine Mechanical Loads Using Engineering Model Predictive Wind Farm Controller

J. Kazda, K. Merz, J. O. Tande, N. A. Cutululis

DTU Wind Energy, Technical University of Denmark

Contents

Motivation and objectives
Wind farm controllers
Case studies

Motivation

- Interaction of wakes with downstream turbines causes up to 80% higher fatigue loads
- O&M costs amount for large share of offshore wind farm lifetime costs
- Wake-induced fatigue loads can be reduced using optimal wind farm controller (WFC)

Objectives

Reduce wind turbine fatigue loads during wind farm ancillary services

- Develop model predictive wind farm controller (MPC) for this operational objective
- Compare performance of MPC with other commonly used wind farm controllers

Wind Farm Controllers: PI-Controller

- Dispatch function sets distribution of total demanded power to individual turbines

Wind Farm Controllers: Engineering Model Predictive Controller

- MPC cost function objectives are to
  - follow total wind farm power reference
  - follow optimum turbine operation point derived from statistical fatigue load models
  - reduce gust-driven mechanical loads
- Model predictive controller estimates wind farm operation using
  - linear, dynamic wind farm flow model
  - statistical and deterministic turbine load model

WFC

predicted state  
actual state  
predicted state  
actual state  

Measured past  Prediction horizon  Unpredicted future  Time
Controllers Tested in SimWindFarm Simulation Tool
- SimWindFarm can perform simultaneous, dynamic simulations of
  - wind turbines
  - wind farm controller
  - aerodynamic interaction of wind turbines
- Controllers are tested through DTU Wind Farm Control framework
- All simulations use wind conditions of
  - mean wind speed of 8 m/s
  - turbulence intensity of 6%
  - constant wind direction along turbine row

Design of Linear Dynamic Wind Farm Operation Model
- Inlet wind speed at downstream turbine is obtained as
  \[ \bar{u}_{in} = \bar{u} + \delta u \]
- Wind speed deficit from upstream turbine is calculated as
  \[ \delta u = \frac{\bar{u} - u}{\bar{u} + u} \]
- State space delay model is used to account for duration of wake propagation

Resulting total system description of flow model is
\[
\begin{align*}
\dot{P}_{\text{uf}} &= A P_{\text{uf}} + B P_{\text{uf}} + C u_{\text{uf}} \\
\end{align*}
\]

Successful Validation of Linear Operation Model
- Linear operation model compares well with SimWindFarm
- Comparison is conducted on array of 8 turbines

Turbine Fatigue Load Model Developed
- Turbine tower fatigue load model is derived from SimWindFarm simulations of two turbine array
- MPC uses optimum operation point determined from fatigue load model

Two-Turbine Case Study
- Performance of MPC and PI-controller are compared in simulations of two turbine array
- Dispatch functions used in PI-controller are
  - static dispatch (WT1: 20%, WT2: 80%)
  - proportional dispatch

Two-Turbine Case Study: Results
- Model-predictive control approach reduces total turbine fatigue loads by up to 28% in this case study
Eight-Turbine Case Study: Set-up

Performance of MPC and PI-controller are compared in simulations of eight turbine array.

Eight turbine array configuration is representative of common offshore wind farms.

Dispatch functions used in PI-controller are:
- static dispatch
- proportional dispatch

Eight-Turbine Case Study: Results

Model-predictive control approach reduces total turbine fatigue loads by up to 25% in this case study.

Conclusions

Developed linear wind farm operation model is successfully validated against SimWindFarm.

Developed turbine fatigue load model can be used in total power reference following WFC to reduce turbine fatigue.

Simulations of developed model predictive controller show up to 28% lower fatigue loads than with other commonly used wind farm controllers.

Two Turbine Case Study

Variations of total power are within Danish grid code limits.

Danish grid code specifies limit of 5% of rated wind farm power as maximum deviation from total power reference.
An approach to linear analysis of wind power plant dynamics, stability, and control

Karl Meier
SINTEF Energy Research

Deepwind, January 19, 2018.

STAS-WPP: Unified state-space model of a wind power plant

Tangent dynamics

\[
\begin{align*}
\frac{dx}{dt} &= f(x, u, t) \\
y &= g(x, u, t) \\
dx_0 &= f(x_0, u_0, t_0) \\
y_0 &= g(x_0, u_0, t_0) \\
d\Delta x &= A \Delta x + B \Delta u \\
d\Delta y &= C \Delta x + D \Delta u
\end{align*}
\]

*\( x_0, u_0, t_0 \) is an initial condition. It does not need to be an equilibrium point.*
Characterization of nonlinearity in wind power plant dynamics

Two different codes, models built by two different analysts.

What is nonlinearity and what is modelling error?

The new version of STAS provides nonlinear and linear equation sets that agree, at the point of linearization, to machine precision. Perturbed solutions will show explicitly the influence of nonlinearity.

Stochastic dynamics of linear systems

In the frequency domain, stochastic leads and fatigue cycle counts are numerically smooth and deterministic: no random numbers.

Modal analysis, explanations of cause and effect in WPP dynamics

<table>
<thead>
<tr>
<th>Mode</th>
<th>Tension side-side modes</th>
<th>Tension flow modes</th>
<th>Damping flow modes</th>
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<tr>
<td>9</td>
<td>0.249</td>
<td>0.249</td>
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</tr>
</tbody>
</table>

Tangent dynamics: applications in the optimization of wind power plants

Define $\lambda.$

Evolution equation for the gradient of the cost with respect to some parameters $\eta.$

Formal model reduction

Starting high-resolution and reducing, we can check that we don't miss any important dynamics.
A generic wind farm controller architecture has been adopted with the following attributes.

- It is hierarchical, decentralised and scalable.
- Top layer responds to grid requirements to determine an adjustment in the power output from the wind farm.
- It may operate open-loop, e.g., to reduce the power output by a fixed amount, or closed-loop, e.g., to curtail the output from the farm to a fixed power level. The latter feedback is based on feedback of the total farm output.
- Second layer determines change in power required from each turbine.
- Bottom layer is a generic interface to each turbine, the PAC.
- The only feedback permitted from each turbine to the first and second layers are flags containing information on the state of the turbines and an estimate of the local wind speed.

This hierarchical structure of the wind farm controller ensures that the turbine controllers are not compromised:

- The wind speed estimation is sufficiently good not to be influenced by the state of the turbine.
- The use of flags avoids the introduction of feedbacks based on the state of the turbine.
- The farm level feedback acting on the total power introduces feedback round a single turbine but weakened by the inverse in the number of turbines.

Tight control at the wind farm level can, thus, be achieved with very weak control of each turbine.
The PAC has the following attributes.

- The PAC does not compromise the turbine controller since it is essentially feed forward in nature.
- It can be interpreted as changing the set point or operational strategy of the wind turbine albeit in a continuous and dynamic manner.
- The turbine is kept within a safe operating region through the use of the flags.
- The change in output power from the turbine matches very accurately the change in power requested.
- Response of the turbine to the requested change can be very fast.
- Very little information about the turbine is required. No information is required on turbine dynamics or the turbine controller.
- It is easily retrofitted.

- Maximum difference is -0.2dB
- So PAC acts as feedforward
Power Adjusting Controller (PAC)

- Flexibility of operation achieved by continuously varying the operating strategy
- The operating strategy curve has been replaced by a region.
- Traffic light system used to keep within safe operating region

Normal operating strategy

Applications

- Individual turbine behaviour
- Traffic light boundaries constrain operational state

Increase in output power

Full envelope controller mode switch

- 5MW wind turbine in 9m/s mean wind speed

Ancillary Services

- Delivery of full range of ancillary services at the wind farm level has been demonstrated
  - Curtailment, droop control and synthetic inertia, etc
- No recourse to modifying turbine’s converter or controller
- Advantages compared to single turbine provision of AS
  - Turbines can compensate each other
  - Only very weak feedback round turbines required
- No significant increase observed but more detailed assessment required
- Issues related to communications delays and grid frequency measurement addressed by Generator-Response Following concept
- Lab based demonstration of GRF being conducted
Applications

Power optimisation and minimisation of loads
- Extent of benefits not clear
- More detailed assessment required
- Need a suitable wind simulation tool – StrathFarm

Wind Farm Simulation Tool
- StrathFarm

Wind Farm Simulation Tool
- Comparison of blade RBMs to Bladed (---) at 15m/s
- Out-of-plane blade RBM
- In-plane blade RBM

Wind Farm Simulation Tool
- Comparison of tower loads to Bladed (---) at 15m/s
- Fore-and-aft tower RBM
- Side-to-side, tower RBM

An analysis and design wind farm model and simulation tool is required with the following requirements
- Model wakes and wake interactions
- Model turbines in sufficient detail that tower, blade and drive-train loads are sufficiently accurate to estimate the impact of turbine and farm controllers on loads.
- Include commercial standard turbine controllers.
- Include wind farm controller and interface to turbine controllers.
- Very fast simulation of large wind farms; run in real time with 100 turbines on a standard PC.
- Flexibility of choice of farm layout, turbines & controllers and wind conditions direction, mean wind speed and turbulence intensity.

All above requirements have been met by StrathFarm
Wind Farm Simulation Tool

The generic controller architecture has been tested

Example
- 5x5MW turbines curtailed to 9MW
- Mean wind speed 9m/s, TI 2%

<table>
<thead>
<tr>
<th>WT Number</th>
<th>Mean Power Produced [MW]</th>
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<tr>
<td></td>
<td>No Curtailment</td>
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<td>4.5</td>
<td>16.0</td>
</tr>
<tr>
<td>5</td>
<td>16.5</td>
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</table>

<table>
<thead>
<tr>
<th>WT Number</th>
<th>DEL In-Plane Blade RBM</th>
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<tbody>
<tr>
<td>4.5</td>
<td>106</td>
</tr>
<tr>
<td>4.58</td>
<td>116</td>
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<td>4.63</td>
<td>166</td>
</tr>
<tr>
<td>4.64</td>
<td>176</td>
</tr>
</tbody>
</table>

Average power Strategy 1Strategy 2

DEL tower fore-aft RBM

Next steps
- Enhance its batch processing capability
- Add power systems aspects to cater for grid events
- Improve the modelling of wakes

Conclusion

- A general purpose controller architecture has been developed and demonstrated to be very effective.
- It’s hierarchical, decentralised and scalable
- A fast wind farm simulation tool has been developed for wind farm control design studies
- Capable of simulating 100 turbines in real time on a standard PC

Acknowledgements

The following funding is gratefully acknowledged
- EPSRC EP/G037728/1 DTC Wind Energy Systems
- EPSRC EP/L016680/1 DTC Wind and Marine Energy Systems
- EPSRC EP/H018662/1 Supergen Wind Phase2
- EPSRC EP/L014106/1 Supergen Wind Hub
- EPSRC EP/N006224/1 MAXFARM
- FP-ENERGY-2013.10.1.6: 609795 IRPWind

and the contributions from
- Adam Stock, Victoria Neilson, Lourdes Gala Santos, Saman Poushpas, Sung-Ho Hur, Giorgio Zorzi, Lindsey Amos, Velissarios Kourkoulis and David Campos-Gaona
Closing session – Strategic Outlook

WindBarge: floating wind production at intermediate water depths, J. Krokstad, NTNU

OO-Star Wind Floater – The cost effective solution for future offshore wind developments, Trond Landbø, Dr.techn. Olav Olsen

The first floating wind turbine in France: Status, Feedbacks & Perspectives, I. Le Crom, Centrale Nantes

Progress of EERA JPwind towards stronger collaboration and impact; Peter Hauge Madsen, DTU Wind Energy

EERA DeepWind’2018 – Closing remarks, J.O. Tande, SINTEF Energi
EERA DeepWind’18
WindBarge - Floating wind production at intermediate water depths

Reduce cost:
- Easy to build
- Easy to install
- Maintain and decommission

TEAM
Jørgen Ranum-Eklostad
Inventor, Prof II Dep. Marine Technology
32 yr. of experience in hydrodynamics and wind

Jan Tore Horn
PhD at Dep. Marine Technology. Focusing on hydrodynamics and reliability.

Synne Nybø

Fredrik S. Moen
Project Manager
International rig management and shipyard experience

WindBarge
- Floating wind barge - easy to install, maintain and decommission
- Water depths 40 – 100 meter
- Large marked within existing farms
- Possible to compete with fixed monopile foundations: more environmental friendly and lower cost
- Low draft - built in standard harbors or docks
- Increased production

Single line mooring and weathervaning

No pretension
No swivel
Redundancy
Position kept by using yaw controller
Known principle
Standard turbine

Expected CAPEX WindBarge versus XL - Monopile

Steel mass ratios compared with competitors

Reference monopile
- Turbine Vestas 164 - 8 MW
- Mass/MW ratio monopile = 244

WindBarge 8 MW
- Turbine Vestas 164 - 8 MW
- Mass/MW ratio WindBarge = 238
WindBarge – Sheltered access

- Sheltered access in the stern of the floater for maintenance vessels (example EDNA – daughter ship (SES))
- Increased weather window
- Target 2.5m Hs

Suction anchor – not new to the wind industry

- High vertical load capacity
- Safety factor of 3 = 8 MN vertical load
- Anchor mass in order of 100 tons
- Towing installation method

Main dimensions – 5 MW version (could be scaled to 8 MW – estimated 1700 ton steel)

Natural Periods
- Heave: 7s
- Pitch: 17s
- Roll: 24.4s

Suction anchor – not new to the wind industry

- High vertical load capacity
- Safety factor of 3 = 8 MN vertical load
- Anchor mass in order of 100 tons
- Towing installation method

Intact stability

- DNV requirements satisfied in pitch.
- In roll, it is assumed that 50% of the capacity is sufficient due to limited wind overturning moment.
Planned Projects

- Verification from simulations/model tests
- General design improvements
- Technology qualification
- LCOE – documentation

WindBarge
Economical floating wind production at intermediate water depths
Fredrik.s.moen@ntnu.no
jorgen.r.krokstad@ntnu.no

Metocean parameters
INTRODUCTION - MAIN MESSAGES

> We believe floating wind will beat onshore wind as well as bottom fixed offshore wind in the future.
> We believe that in the future there will be three different segments within the wind industry:
  - Onshore wind; WTGs limited to typically 5 MW due to transport and installation limitations on land.
  - Offshore wind, bottom fixed; WTGs limited to typically 10 MW due to installation cost.
  - Offshore wind, floating; WTGs typically 20 MW, no size limitations related to assembly and installation.
> We believe Dr.techn. Olav Olsen has developed a very cost effective floating solution with the OO-Star Wind Floater, with all the qualities required by the future floating offshore wind market.
BUSINESS AREAS

- Buildings onshore
- Offshore Oil & Gas
- Renewable energy
- Infrastructures
- Harbours and Industry
- OO «Futurum»

Core business: Structural & Marine engineering

Adding value to company and clients

OLAV OLSEN - CAPABILITIES OFFSHORE WIND

- Substructures
  - Bottom fixed and floating
  - Steel and concrete
  - Concept development
  - Design and analysis (ShellDesign)
  - Geotechnics
- Mooring and anchors
  - System configuration
  - System design
  - Geotechnics
- Installation
  - Method development
  - Installation concepts
- Fully coupled simulations:
  - SIMA
  - 3DFloat
  - Deeplines
  - (Orcaflex, Ashes, FEDEM Windpower)
- Cost models
  - Fabrication and installation
    - Substructure
    - Mooring
    - Anchors
- Third party verification

OLAV OLSEN - OFFSHORE WIND

FLOATING OFFSHORE WIND TURBINES

Hywind
Hydro/StatOil
HIPRWind
EU project
OO Star Wind Floater
Patented concept

OO-STAR WIND FLOATER
THE OO-STAR WIND FLOATER HISTORY

- Few realistic WTG floaters before 2010
- Hiprwind (2010) - questions to scalability and fatigue
- What does the optimal floater look like?
- OO-Star Wind Floater developed 2010/11, presented at ONS2012
- Preferred concept (steel) for EU project Floatgen - Acciona part 3 MW WTG
- NFR project 2013-2014: Designed for 6MW, WD 100 m, North Sea
- LIFES50+ 2015-2018: Up-scaling to 10 MW, WD 70-130 m, Hs=7.0 -15.6 m

MOORING - BASIC CONFIGURATION

- 3 line system
- GoF and GoM: Chain catenary with Clump weight
- Focus on new development
  - Line configurations
  - Number of lines
  - Line materials
  - Anchor types and sharing

OO-STAR OFFSHORE WIND FLOATER

- Robust, stable and very simple 3-leg semisubmersible floater.
- Passive ballast system
- Water depth potential from 50 m
- Concrete, steel or a combination (hybrid). Material selection according to optimal design, cost, fabrication facilities etc.
- Concrete best suited for large wind turbines. Not fatigue sensitive and long design life: 100 years +. Possible to reuse floater.
- The OO-Star Wind Floater consists of a central shaft supporting the WTG, and a tri-star shaped pontoon supporting 3 buoyancy cylinders for optimal stability.
- Permanent buoyancy in the columns and shaft. The pontoons provide structural support of the columns, weight stability, damping/added mass and temporary buoyancy for inshore assembly.
- Fabrication in a dock, on a barge or on a quay. The structure is well suited for modular fabrication.
- The substructure can float with very small draft and the unit can be fully assembled at quay-side before tow to site. No requirements for deep waters at assembly site.
- Transport to site by towing. No requirements for expensive offshore heavy lifts.

HORIZON 2020 - LIFES 50+

- Horizon 2020 project, total budget 7.3 M€uro
- Project lead by SINTEF Ocean
- OO Star Wind Floater selected as one of two concepts for Phase 2 (model testing and further development)
- Project web page: http://lifes50plus.eu

LIFES 50+ MODEL TESTS

- Modell tests planned in Phase 2:
  - Ocean Basin at SINTEF Ocean, November 2017 (Scale 1:36)
  - Wind tunnel at Polimi, Spring 2018 (Scale 1:75)
FABRICATION/INSTALLATION
OO-STAR WIND FLOATER

ASSEMBLY AT QUAYSIDE – CURRENT WTG’S

ASSEMBLY AT QUAYSIDE – FUTURE LARGE WTG’S

FABRICATION SET-UP

FABRICATION 25 UNITS/YEAR – TYPICAL SCHEDULE

BOTTOM FIXED WTGS (FOR COMPARISON)

FABRICATION/INSTALLATION – CHALLENGES
OFFSHORE WIND - BOTTOM FIXED

GBS Production Facilities – Large Scale

Main challenges:
- Variations in GBS configuration
- Flexibility of yard set, water depth at site and soil conditions
- Water depth at keystone and loading draft – stability issues
- Large site investment required, few sites suited

Conclusion:
- Difficult to industrialize fabrication process
- Full mature assembly is not cost-effective for GBS since floating stability will be the main design parameter, not the operation phase.
- Alternative: Offshore assembly

SPACE FRAME TOWER (SFT)

> Foundation - different solutions
  - Gravity base
  - Suction buckets
  - Piles

> 3 main element types:
  - Vertical legs, constant diameter
  - X and K nodes with uniform design. Cost effective fabrication, superior fatigue capacity
  - Uniform X-bracing system

> Transition structures are standardized for turbine type

SFT - NODE FABRICATION

Proposed Fabrication scheme for SFT substructure

Conclusion:
- Easier than GBS to industrialize the fabrication process
- Will depend on offshore assembly or special installation vessels

SUMMARY BOTTOM FIXED

> Monopiles have been dominating the market for bottom fixed offshore wind – highly industrialized
> Jacket structures becoming more popular for deeper water and larger WTGs, less steel than monopoles give potential for cost savings.
> Use of concrete can increase the operational life of substructures
> Difficult to standardize bottom fixed substructures due to variation in water depth, soil conditions and environmental loading
> Monopiles and jackets have higher potential for standardization and industrialization than concrete GBS
> Installation of bottom fixed WTGs requires offshore assembly or costly measures to solve temporary conditions.
> Future large WTGs (20 MW) will require expensive new installation tools. Likely that bottom fixed WTGs will be limited in size.
OFFSHORE WIND CHALLENGES

The main and overall challenge is to reduce cost of energy (LCOE) – cannot rely on subsidies in the future.

Requirements:
- Consistent frame conditions (political, consenting, tendering process, environment etc.)
- Development of consistent rules and regulations
- Development of business tools (financing, insurance etc.)
- Development of supplier industry (competition, effectiveness, market stability)
- Development of new and better technology
  - Economy of scale, larger turbines
  - Increase efficiency, robustness and operation life
  - Reduce CAPEX, OPEX
- Development of fabrication and installation methods (reduce CAPEX, risk)

Floating wind has larger energy potential than bottom fixed.
In some areas floating wind is the only way to go. This will ensure development of a floating market.
Floating substructures have higher potential for standardization than bottom fixed (not very sensitive to water depth and soil conditions). Efficient and cost-effective mass fabrication of substructures.
Shallow draft floaters - Quayside assembly and testing prior to tow out
Installations without offshore heavy lift – tow to site
Simple removal – reverse installation
Large potential for reuse - 2nd hand value of floater will reduce energy cost
Large potential for efficient supply chain and significant cost reductions
Robust execution program suitable for future large W TGs
Next generation 20 MW floating W TGs can be assembled without expensive new offshore cranes
Specific for Norway:
- Norway do not have suitable sites for bottom fixed offshore wind (with a couple of exceptions).
- Floating wind has a significant future potential in Norway.

WHY FLOATING OFFSHORE WIND WILL OUTFIT BOTTOM FIXED OFFSHORE WIND IN THE FUTURE

FLOATING WIND – KEY ADVANTAGES
- Floating wind has larger energy potential than bottom fixed.
- In some areas floating wind is the only way to go. This will ensure development of a floating market.
- Floating substructures have higher potential for standardization than bottom fixed (not very sensitive to water depth and soil conditions). Efficient and cost-effective mass fabrication of substructures.
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WHY OO-STAR WIND FLOATER HAS THE QUALITIES REQUIRED BY THE FUTURE OFFSHORE WIND MARKET

OO-STAR WIND FLOATER

Has the qualities required by the future offshore wind market.
OO-STAR - ADVANTAGES

- OO-Star Wind Floater is a simple and robust floater concept, with favourable motions for WTG and cable
- Adaptive to «all» environmental conditions and WTG sizes
- Very good «scalability-factor» for increase of WTG size
- Concrete is less sensitive to fatigue than steel (WTGs are fatigue machines) and requires minimum maintenance
- Concrete substructure has long design life, 100+ years with minor cost increase (concrete cover, cathodic protection and outfitting)
- Concrete is fabricated in all countries, limited number of skilled workers required
- Shallow minimum draft – can be fully assembled and tested at quayside
- No offshore heavy lifts – WTG assembly by land cranes onto fixed substructure (resting at seabed)
- Mooring connections above water – easy access and «artificial» increase of water depth (benefit for mooring in shallow water)
- Fixed mooring points at 2 columns, fairlead/chain stopper at 3rd column. Tensioning from vessel, no winch.
- Possible to improve cost and durability by lifting interface between concrete and steel and to reduce steel tower fatigue (crucial for future large WTGs)

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The first Floating Wind Turbine in France (SEM-REV)

I. Le Crom, ECN, EERA Deepwind 19/01/2018

Offshore Wind Resource in France

- Installed Onshore: > 13.7 GW
- Forecasted Offshore: > 3.1 GW

France is investing

- Fixed offshore wind turbine: > 80 GW over 10 000 km²
- Floating wind turbine: > 140 GW over 25 000 km²

FOW: 1st pre-Commercial Farms in France (EOLFLO)

- Groix: 4 x 6 MW
- Commissioning expected in 2020
- 3 floater technologies
- Perspective: 6 GW in 2030

Introduction

- CENTRALE NANTES and SEM-REV Test Site
- LHEEA Laboratory
- SEM-REV
- Floatgen Project
- Floatgen FWT
- Status
- LHEEA R&D Roadmap
- Research Program
- Feedback & Perspectives

BFLOW: 1st Commercial Farms in France

- 1st Call: commissioning expected in 2020-2022
- 2nd Call: commissioning expected in 2021-2023
- Perspective: 15 GW in 2030

Groix

Perspective: 15 GW in 2030

Groix

4 x 6 MW

Commissioning expected in 2020

3 floater technologies

Perspective: 6 GW in 2030
**Centrale Nantes**

- Graduate engineering programs, Masters and PhDs, to French and international students (2000 students)
- Mechanics, Materials, Energy, Cybernetics, Architecture
- 250 teaching and research staff, 38 partners countries
- 50% R&D budget in collaborative projects with industry

> Widespread recognition of the institute by firms and R&D organizations has enabled graduates to assume positions of responsibility in every sector...

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**LHEEA**

Strategy to support R&D projects and technology development to make the MRE economically viable

- By using large scale numerical and testing facilities
- Validation of numerical methods and model tests vs results in real conditions

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**SEM-REV : Overview**

- CAPEX: 20 M€
- 12nm from Le Croisic
- 1 km² restricted area
- 35m LAT

**Floatgen Project**

Demonstrate the technical and economic feasibility of one multi-MW integrated floating-wind turbine in the Atlantic Ocean conditions

Industry-led European initiative with partial public support

IDEOL

Design: Floater, Umbilical, Configuration & Moorings, Pre-Lay Method & Hook-Up

Bouygues TP

Floater Construction, ECN, Interface with Environment

---

**Floatgen**

- Ø = 80m Wind Turbine
- 2 MW
- Concrete floating foundation (Damping Pool ® system designed by Ideol)
- h = 9.5m, 36m wide
- Draught in place 7m

Main steps:
- 2009 – Test site monitoring,
- 2012 – Export cable,
- 2015 – Subsea hub

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**SEM-REV**

- General view of marine social sciences: consenting, permitting, environment, safety
- Responsible for the procurement & installation of Electrical connection + Moorings
- Design by IDEOL

Actual State

Instrumentation
- Export Cable
- Junction Box
- Hub
- Umbilical

Moorings (6 lines)
- Drag embedded Anchor – chain – synthetic rope
Floatgen Installation

To do List
- ML Hook-Up
- Umb Hook-Up
- Instrumentation

R&D P1: Marine environment and resources

Environmental Monitoring Plan
- Marine life, Birds,
- Marine Growth
- Corrosion and Abrasion
- Anodes, Paints: water
- Bathymetry, sediments
- Power cables impacts
- Marine operations, O&M
- Marine traffic (risk an.)

Supporting R&D
- Marine environment and resources
  - Environmental Monitoring: SEA-MON, MOSAIC
  - Marine growth: ABIOP, LEHERO
  - Soil mechanics: EOGP
  - Environmental impacts: SPECIES
- MRE Technologies (FOWT, WEC)
  - Floating wind demonstration (FLOATGEN)
  - FOWT components and Performances (FORESEA)
- Energy Conversion, Transport and Storage
  - Subsea connection units: HUB
  - Export and Dynamic Cables: EMODI, OMDYN
- Security, Safety, Marine operation
  - Health Monitoring: MM-EMR
  - Marine operation and O&M: HUB installation
Demonstration and Access to Market
FORESEA, MARINETII projects

FORESEA under Interreg NWE program
- Supporting LCT developers to access NW Europe’s test facilities
- SME / LCT : New Techno, PTO, Mooring, Umbilicals/connectors,
- Test sites benchmarking, Technologies vs market
- From 02/2016 to 12/2019
- Co-Funding of testing cost up to 60%

MARINET 2 under M203 Program
- Supporting MRE developers to access Europe’s test facilities
- Funding : 100% of the test site cost (directly to the test site)

MARINERG-I / ESFRI : French national Research Infrastructure
- Ifremer + Centrale Nantes MRE testing facilities

R&D P3 : Energy Conversion, Transport and Storage

OMDYN project
Dynamic cables: from cores to armors
- Mechanical characteristics of cable components
- Loads, motions and deformations
- Influence of marine growth
- Default diagnostic
- Cables stabilization on sea bed

Numerical, Bench test, Model Tests
- Numerical modeling of the global configuration and cross section
- Experimental analysis of thermo-mechanical fatigue
- Forced and free dynamic response

In-situ monitoring
- Monitoring throughout the cable life cycle

With : Un Nantes / GeM, IREENA, MMS, IFSTTAR,
Ifremer, CEA Tech, RTE, DCNS, EDF, IFSTTAR, Nexans, Ideol,...

R&D P4 : Security, Safety, Marine operation

Floatgen
Pre-Lay Methodology
- Anchors Positioning & Pre-stretching
- Deployment
- Recovery
- Tensioning
- Abandonment

Modelling of marine operations
- Operations improvement
- Embarked Real-time Calculation

FRYDOM project
- Multibody dynamics
- Cable dynamics
- Unsteady / transient responses
- Waves and wind loads
- Water entry/impact
- Controllers (crane, turbine, winch)
- Dynamic positioning
• General overview of the challenges
• Targeting the cost reduction of MRE
  • From TRL 1 to TRL 8
• Attractive Research Platform for MRE
• Open to host other concepts or projects

www.semrev.fr
Progress in EERA JP Wind towards stronger collaboration and impact

SINTEF-DTU partnership for offshore wind energy

Peter Hauge Madsen
Director, DTU Wind Energy & Coordinator of EERA JP WIND
Deepwind conference 2018
Trondheim

Why collaborate (more)?

MEGATRENDS
- Maturation, Industrialisation and Globalisation
- Subsidy free wind power and technology
- Neutral Tenders
- Digitalisation
- Energy Systems Integration

Different modes of scale & consolidation

Companies merge

Public Research organisations collaborate

EERA JP WIND - a vehicle for collaboration
- EERA is an organisation under the EU SET-Plan
- EERA JP WIND 1 of 17 Joint Programmes
- 50 member organisations
- Building trust & knowledge exchange
- Major EU projects setup through EERA JP WIND collaboration
- IRPWND project supporting JP WIND coordination and research

Summary - 8 years of learning
- 8 years of coordination growing from 13 to 50+ participants

• General value and impact from
  - Strategy and policy
  - Platform for coordination
  - Data and facility sharing
  - Knowledge sharing
  - Mobility and community building

• Challenges
  - Alignment of national programmes
  - Leveraging “own resources” in joint activities
  - Wide involvement in industry cooperation
  - Managing expectations

DTU Wind Energy, Technical University of Denmark
Working together in Europe

- In width and setting the EU Strategy
- In depth and working with industry
  - Individually
  - Ad-hoc
  - Strategic partnerships

Strategic areas of collaboration
- Offshore wind energy

Offshore grid development
Wind farm control
Wind turbine substructures

Why DTU and SINTEF?

Complementary competence profiles

DTU
A leader in wind energy research including wind turbine loads and control, aerodynamics, and resource assessment.
Operating three wind turbine test sites in Denmark and turbine technology lab.
PhD and MSc education
Total staff of about 5900 (incl. approx. 1200 PhD students)

SINTEF
Strong competence on offshore wind technology, including substructures, O&M, materials, grid connection and control.
Relevant laboratories include ocean basin and smart grids.
Strong collaboration with NTNU for PhD and MSc education
Total staff of about 2000

Key elements in the partnership
- Focus on key offshore wind challenges
- Partnership for building strength and value
- Commitment to cooperate and coordinate
- Joint roadmap for research
- Transparency and openness within partnership
- Flexible funding approach
- Non-exclusivity and open for collaboration with others

Targeting industry R&D needs

Perspective
- Serving offshore wind industry needs
- A step towards European R&I integration
  - Institutional alignment
  - Public-private collaboration
- Wider knowledge and service portfolio
  - From research to demonstration
  - From education to testing
  - From lab to full scale

Challenges
- Culture
  - From national to international outlook
  - From personal to institutional collaboration
- Administrative issues
  - Aligning national funding
  - Legal
  - Cost and overhead
International collaboration is the new norm

*Let us pave the way*
NOWITECH has 40 innovations in progress

NOWITECH (2009-2017)

- A joint pre-competitive research effort
- Focus on deep offshore wind technology (+30 m)
- Budget EUR 40 millions
- Co-financed by the Research Council of Norway, industry and research partners
- 25 PhD/post doc giants

- Key target: innovations reducing cost of energy from offshore wind
- Vision:
  - large scale deployment
  - internationally leading

Research partners:
- SINTEF Energy (Lead)
- SINTEF Ocean (MARINTEK)
- SINTEF Foundation
- DTU Wind Energy
- Michigan Tech Univ.
- MIT
- NREL
- Fraunhofer IWES
- Uni. Strathclyde
- TU Delft
- Nanyang TU
- ASHES (SIMIS AS)
- www.ashes.no

Industry partners:
- DONG Energy
- Fedem Technology
- Fugro OCEANOR
- Kongsberg Maritime
- Norsk Automatisering
- Statkraft
- NCEI
- NORWEA
- NVE
- Wind Cluster Norway
- Devold AMT AS
- Energy Norway
- Enova
- NCEI
- NVE
- Wind Cluster Norway
- SINTEF Ocean (MARINTEK)
- SINTEF Foundation
- DTU Wind Energy
- Michigan Tech Univ.
- MIT
- NREL
- Fraunhofer IWES
- Uni. Strathclyde
- TU Delft
- Nanyang TU
- ASHES (SIMIS AS)
- www.ashes.no

Associated research partners:
- ZE (Material Research)
- MHI
- Ramboll
- Foundation (RMI)
- NKT Cables
- NTU (China)
- Ningbo TUI

Associated industry partners:
- Simula (IT Centre)
- SINTEF Oil and Gas
- Energy Norway
- MoD
- Innovation Norway
- MEST
- NVE
- NRK
- Wind

Why continue NOWITECH as a research network?

- Leverage on results from NOWITECH
- Keep momentum in cooperation
- Increase visibility and impact
- Enhance dissemination and communication of results
- Organize ERA DeepWind
- Share open research and data
- Joint publications

Potential value of innovations

NPV: > 5000 MEUR*

* Result from analysis carried out by Impello Management AS for a subset of innovations by NOWITECH. NPV is calculated as socio-economic value of applying the innovations to a share of new offshore wind farms expected in Europe until 2030.

Leverage on results from NOWITECH
- Share scientific advice and research strategies
- Align with EERA JPwind
- Collaboration across projects
- Attract funding
  - Access to research facilities
  - Facilitate researcher mobility
- Joint R&D projects
  - ...
• Research network sharing open results
• Focus on deep offshore wind technology (+30 m)
• Budget in-kind by the individual partners, possibly with additions from the Research Council of Norway and industry
• Key target: increasing the economic attractiveness of offshore wind through generation of new knowledge, models, processes and technology
• Vision:
  • large scale deployment
  • internationally leading

NOWITECH research network

• National network with international participation
• Non-exclusive
• Volunteer basis
• National meetings 4-6 times per year, physical or by skype
• International meeting 1-2 times per year, aligned with EERA Deepwind and other events, possibly also outside Norway
• Lean structure (management board + general assembly)
• Participation by invitation
• Commitment by LoI
• ...
Poster session

Session A
1. **Load estimation and O&M costs of Multi Rotor Array turbine for the south Baltic Sea**, M. Karczewski, Lodz University of Technology
2. **Dynamic Responses Analysis for Initial Design of a 12 MW Floating Offshore Wind Turbine with a Semi-Submersible Platform**, J. Kim, University of Ulsan, Korea

Session B
3. **SiC MOSFETs for Offshore Wind Applications**, S. Tiwari, NTNU/SINTEF Ocean

Session C
4. **Extreme met-ocean conditions in a Norwegian fjord**, Z. Midjiyawa, Meteorologisk institutt
5. **Modelling of non-neutral wind profiles - current recommendations vs. coastal wind climate measurements**, P. Domagalski, Lodz University of Technology
6. **Uncertainty estimations for offshore wind resource assessment and power verification**, D. Foussekis, Centre for Renewable Energy Sources

Session D
7. **Using a Langevin model for the simulation of environmental conditions in an offshore wind farm**, H. Seyr, M. Muskulus, NTNU

Session E
8. **Design optimization with genetic algorithms: How does steel mass increase if offshore wind monopiles are designed for a longer service life?**, L. Ziegler, Rambøll Wind
9. **Experimental Study on Slamming Load by Simplified Substructure**, A. Krogstad, NTNU
11. **Supply chains for floating offshore wind substructures - a TLP example**, H. Hartmann, University Rostock
12. **Critical Review of Floating Support Structures for Offshore Wind Farm Deployment**, M. Leimeister, REMS, Cranfield University
13. **Assessment of the state-of-the-art ULS design procedure for offshore wind turbine sub-structures**, C. Hübler, Leibniz Univ Hannover
15. **State-of-the-art model for the LIFESS0+ OO-Star Wind Floater Semi 10MW floating wind turbine**, A. Pegalajar-Jurado, DTU
16. **Validation of a CFD model for the LIFESS0+ OO-Star Wind Floater Semi 10MW and investigation of viscous flow effects**, H. Sarlak, DTU
17. **Designing FOWT mooring system in shallow water depth**, V. Arnal, LHEEA, Centrale Nantes
18. **Construction Possibilities for Serial Production of Monolithic Concrete Spar Buoy Platforms**, C. Molins, UPC-Barcelona Tech
20. **Fabrication and Installation of OO-Star Wind Floater**, T. Landbo, Dr. techn. Olav Olsen

Session F
21. **Experimental validation of analytical wake and downstream turbine performance modelling**, F. Polster, Technical University of Berlin
22. **Reduce Order Model for the prediction of the aerodynamic lift around the NACA0015 airfoil**, M. S. Siddiqui, NTNU
23. **Fast divergence-conforming reduced orders models for flow**, E. Fonn, SINTEF Digital
Session G
24. Sensitivity analysis of the dynamic response of a floating wind turbine, R. Siavashi, University of Bergen
26. Emulation of ReaTHM testing, L. Eliassen, SINTEF Ocean
27. Multiple degrees of freedom real-time actuation of aerodynamic loads in model testing of floating wind turbines using cable-driven parallel robots, V. Chabaud, NTNU/SINTEF Ocean
28. A 6DoF hydrodynamic model for real time implementation in hybrid testing, I. Bayati, Politecnico di Milano
29. Kalman Estimation of Position and Velocity for ReaTHM Testing Applications, E. Bachmann Mehammer, Imperial College London/SINTEF Energi
30. Numerical modelling and validation of a semisubmersible floating offshore wind turbine under wind and wave misalignment, S. OH, ClassNK

Session H
31. Impact on wind turbine loads from different down regulation control strategies, C. Galinos, DTU
Load Estimation and O&M costs of Multi Rotor Array Turbine for the South Baltic Sea

Maciej Karczewski1*, Piotr Domagalski1, Michal Lipian1, Lars Roar Saetran2
1 Institute of Turbomachinery, Lodz University of Technology, Lodz, Poland, *Email: maciej.karczewski@p.lodz.pl
2 Department of Energy and Process Engineering, Norwegian University of Science and Engineering, 7491 Trondheim, Norway.

Introduction
• Poland experiences energy shortage at northern parts of the country;
• Polish RES bill significantly limited operations for on-shore wind;
• Gov’t plans to support 2-3 shallow off-shore farm locations, but no sight for overall cost reduction and instigation of local heavy industry;
• AIM1: explore deep off-shore wind locations such as our idea of location 4 to show costs can be reduced.
• AIM2: propose floating off-shore wind turbine design in the form of Multi Rotor Array (MRA) to mitigate cost and technology problems.
• AIM3: revitalise Polish shipyard industry around our own MRA concept.

Methodology
• Evaluated benchmark Vestas V100 2 MW turbine for costs at all 4 loco by using NREL design cost and scaling model1;
• Designed a layout of 7 rotor MRA and scaled the baseline NREL 5 MW single rotor turbine2 down to a 0.714 MW;
• Analysed hourly metocean data for the 50-year period;
• Preapred a FAST add-on tool in Matlab and verified structural integrity of MRA rotors using aero-servo-elastic solver FAST ver 8.0 against approved load cases3;
• Measured performance of the proposed MRA and compared it to baseline NREL 5 MW turbine.

Numerical model
• RNA of the baseline turbine was Froude scaled to derive mass of our 1MRA rotor3;
• Steady-state validation of the scaled rotor model made;
• Average/extreme sea state from coastDat1 DB for location 4:
  - Mean wind speed \( V_{ave} = 10.1 \text{ m/s} \), extreme \( V_{max} = 36.7 \text{ m/s} \);
  - Mean signific. wave height \( H_{ave} = 1.2 \text{ m} \), wave period \( T_{ave} = 5.19 \text{ s} \), extreme \( H_{max} = 9.9 \text{ m} \), \( T_{Hmax} = 12.3 \text{ s} \);
• Power law wind shear exponent=0.14 adjusting induction to MRA

Initial results
• RNA of the baseline turbine was Froude scaled to derive mass of our 1MRA rotor3;
• Steady-state validation of the scaled rotor model made;
• Average/extreme sea state from coastDat1 DB for location 4:
  - Mean wind speed \( V_{ave} = 10.1 \text{ m/s} \), extreme \( V_{max} = 36.7 \text{ m/s} \);
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• Power law wind shear exponent=0.14 adjusting induction to MRA

References
Introduction

- Why do we need 12 MW Floating Offshore Wind turbine (FOWT)?
  - Able to use in Deep Water: the stable and strong wind flows.
  - Improve energy production capacity and reduce construction costs.
  - Solution for noise and insufficient space.
- The purpose with the design of a 12 MW UOU(University of Ulsan) FOWT.
  - Desing of FOWTs must consider both aerodynamics and hydrodynamics.
  - The floating platform has the lowest natural frequencies.
  - Initial dimensional design of tower to avoid buckling and resonances.
  - Solution for unstable coupling between platform motion and pitch controller.
- Dynamic responses analysis for initial design of a 12 MW UOU FOWT using fully coupled analysis was performed to determine the suitability.

Design of 12 MW Floating Offshore Wind Turbine

- The initial design of 12 MW UOU FOWT was performed based on a 5 MW NREL wind turbine for offshore model, using geometric laws of similarity.

Design of 12 MW Floating Offshore Wind Turbine

Tower Resonance Analysis

- A tower design is proposed to avoid the 3P resonance problem due to the direct expansion of the 5 MW wind turbine support.

Control system of 12MW FOWT

- In the case of a FOWT, the negative damping problem occurs when applying conventional pitch control system of land-base wind turbine.
- The negative damping has the reducing rated power and increasing fatigue load.
- 12 MW FOWT was modified, the PI controller to avoid negative damping problem and the response speed of the blade pitch controller to be lower than the response speed of the platform.

Numerical simulation

Simulation results

Conclusion

- Initial design of a 12 MW UOU FOWT using fully coupled analysis was performed to determine the suitability.
- Dimensions of tower was approved by buckling analysis.
- 3P Resonance avoided through the redesign of the tower.
- Negative damping was solved through the response speed control of the blade-pitch controller.

ACKNOWLEDGEMENT

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SiC MOSFETs for Offshore Wind Applications

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Norwegian University of Science and Technology, 7491, Trondheim, Norway

Summary- This paper investigates the switching performance of half-bridge SiC MOSFET and Si IGBT modules. Both the modules have same packaging and voltage rating.

Turn-on and turn-off switching energy losses are measured using a standard double pulse methodology. The conduction losses from the datasheet and the switching energy losses obtained from the laboratory measurements are used as a look up table input when simulating the detailed inverter losses in a three-phase grid-side inverter in an offshore wind application.

Simulated inverter loss is verified analytically. The total inverter loss is plotted for different switching frequencies in order to illustrate the performance improvement that SiC MOSFETs can bring over Si IGBTs for a grid-side inverter from the efficiency point of view.

The overall analysis gives an insight into how SiC MOSFET outperforms Si IGBT over all switching frequency ranges with the advantages becoming more pronounced at higher frequencies.

Introduction-

The superior material properties of silicon carbide (SiC) can be translated to switching devices with higher operating temperatures, higher breakdown voltages, lower conduction and switching losses, and higher power density, and thereby fulfil the demand of converters for offshore wind applications. In particular, these converters will be compact, efficient, and thermally stable, and thus can be easily mounted in the nacelle of wind turbine.

Laboratory setup and measurement results-

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Si</th>
<th>SiC</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap (eV)</td>
<td>1.1</td>
<td>3.2 (=2.9 × Si)</td>
<td>Higher operating temperature</td>
</tr>
<tr>
<td>Breakdown electric field (MV/cm)</td>
<td>0.25</td>
<td>3 (=12 × Si)</td>
<td>Higher blocking voltage and lower losses</td>
</tr>
<tr>
<td>Thermal conductivity (W/(cm.K))</td>
<td>1.5</td>
<td>4.9 (=3.2 × Si)</td>
<td>Increased power density</td>
</tr>
</tbody>
</table>

• Key electrical parameters of SiC MOSFET versus Si IGBT module

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CAS300M12BM2 (Wolfspeed)</th>
<th>SKM400GB125D (Semikron)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&lt;sub&gt;ds&lt;/sub&gt;-&lt;sub&gt;rce&lt;/sub&gt; (mΩ)</td>
<td>5</td>
<td>7.8</td>
<td>+36</td>
</tr>
<tr>
<td>V&lt;sub&gt;CEO&lt;/sub&gt; (V)</td>
<td>Absent</td>
<td>Absent</td>
<td>Absent</td>
</tr>
<tr>
<td>R&lt;sub&gt;d&lt;/sub&gt; (mΩ), diode</td>
<td>2.25</td>
<td>4.35</td>
<td>+48</td>
</tr>
<tr>
<td>V&lt;sub&gt;F0&lt;/sub&gt; (V), diode</td>
<td>0.925</td>
<td>0.83</td>
<td>-9</td>
</tr>
</tbody>
</table>

Simulation of inverter loss-

- Conduction loss from datasheet and switching loss obtained from the laboratory measurements are used as a look up table input for simulating detailed inverter loss.

Simulation results-

- P<sub>inv</sub> is about 69 % of total inverter loss at 25 °C for inverter with Si IGBTs at 50 kHz. Thus, Si IGBT is not a viable solution at high switching frequency.

- For the same output power, the inverter switching frequency with SiC MOSFETs can be increased by 5 times and still have the same total power loss.
Analysis of wind shear in Sulafjorden

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¹ Norwegian Meteorological Institute
² Department of Mathematical Sciences, Norwegian University of Science and Technology
³ Geophysical Institute, University of Bergen

Introduction
The E39 is a 1100 km highway route that connects Kristiansand to Trondheim (Figure 1). The E39 connects some of the largest Norwegian cities such as Kristiansand, Stavanger, Bergen, Ålesund, Molde and Trondheim.

The purpose of Ferjefer E39 project is to design a ferry-free highway route. Analysis of wind conditions and wind flow characteristics are essential for bridge design. The present study investigates monthly variability of the wind shear in Sulafjorden (Figure 1), which is one of the Norwegian fjords that E39 crosses. The analysis is based on one year of wind measurements, but the results are illustrated for one month chosen per season.

Theory and Results
The wind profile power law equations is:

\[
\frac{U}{U_f} = \left(\frac{z}{z_f}\right) ^ \alpha
\]

where \(U\) and \(U_f\) are the wind speeds (m/s) at height \(z\) and \(z_f\) (m) respectively. The wind shear or power law exponent (\(\alpha\)) is a dimensionless coefficient that describes the wind shear and is widely used for wind energy applications [2]. The \(\alpha\) exponent is depending on atmospheric stability [3], [4]. For neutral conditions, \(\alpha\) is approximately 0.14 onshore. For offshore conditions, it is suggested that \(\alpha\) equals to 0.11 is a good approximation [5].

For this study, wind measurements at heights 44.5 m and 92.5 m (period: 01.2017-12.2017) from the met mast at Kvinesdal (Figure 2) has been used. The met mast is located at the northwest fjord entrance. Southwest of the met mast, there are mountains with heights of 627 m and 570 m.

Figure 3 illustrates the wind shear exponent as a function of wind direction at 92.5 m for a reference height of 44.5 m for one month per season in 2017. The different color indicates the different wind speed levels.

Figure 4 shows the wind shear exponent as a function of wind speed at 92.5 m for a reference height of 44.5 m for one month per season in 2017. The black color indicates wind directions from 150 to 200 degrees and the blue color wind directions from 250 to 300 degrees.

Location of Measurements

Figure 2. Location of met mast (orange pointer) in Sulafjorden (Source: Kartverket)

Conclusions
The results for Sulafjorden show:
- The strongest winds were mainly observed from southeast and northwest.
- For moderate to high wind speed, the wind shear coefficient tends to decrease to values lower than 0.11 (suggested for offshore conditions).
- For low wind conditions, high absolute values of wind shear coefficient are observed.
- The month of June shows the highest value of wind shear coefficient. The maximum value is 2.51 while the minimum value 0.09 in November.
- The monthly rms value of wind shear fluctuates between 0.09 in November to 0.29 in June, which shows the limitation of using the value of the 0.14 onshore and 0.11 offshore for design purposes.

Acknowledgments
This study is a part of the Ferjefer E39 [1], subproject Fjord Crossing financed by the Norwegian Public Roads Administration (NPRA).

References

Figure 1. E39 highway route (Source: vegvesen.no)

Figure 3. Wind shear exponent as function of wind direction for January 2017 (Top left), March 2017 (Top right), July 2017 (Bottom left) and October (Bottom right) in Sulafjorden

Figure 4. Wind shear exponent as function of wind speed for January 2017 (Top left), March 2017 (Top right), July 2017 (Bottom left) and October (Bottom right) in Sulafjorden for 150 to 200 and 250 to 300 degree in wind direction
Models tested

Stability corrected logarithmic model:

\[ u(z) = \frac{u_z}{k} \left( \ln \frac{z}{z_0} - \Psi(c) \right) \]

\[ \Psi(c) = -4.8(z/L) \]

\[ z/L \geq 0 \]

Panofsky&Dutton model:

\[ \frac{z}{L} / \Psi(z/L) \]

\[ \alpha(z/L) = \frac{\phi(z/L)}{\ln(z/L) - \Psi(z/L)} \]

\[ \phi(z/L) = 1 - \frac{\psi(z/L)}{0} \]

\[ \phi(z/L) = 1 + 4.7(z/L); \psi(z/L) = -4.7(z/L) \]

\[ \phi(z/L) = 0 \]

Peña boundary layer height corrected model:

\[ u(z) = \frac{u_z}{k} \left( \ln \left( \frac{z}{z_0} \right) - \psi(z) \left( 1 - \frac{z}{2z_0} \right) \right) \]

\[ z_0 = 0.1 \cdot 0.25 \cdot \frac{v}{L} \]

Smedman&Högström model:

\[ a = c_0 + c_1 \log(z_0) + c_2 [\log(z_0)]^2 \]

Site, equipment & data description

- 100 m high Met-mast.
- Velocity (Gill Wind Observer IID) & temperature measurements at: 10, 16, 25, 40, 70 and 100 m.
- Pressure & humidity from nearby Sula meteostation.
- Data acquisition time: Nov 2009-Dec 2012.
- Approx. 160000 of 10 min samples for each height.

Atmospheric stability

For atmospheric stability calculations we used the bulk Richardson number as a basis for Obukhov length calculation:

\[ Ri = \frac{\theta_s (\Delta u)}{\theta_v (\Delta u)} \ln \left( \frac{z_1}{z_2} \right) \]

\[ L = \left( \frac{z_1}{z_2} \right)^{0.25} \]

Results

- 5 % underestimation of predicted wind velocity is observed during unstable conditions.
- The deviation grows dramatically up to 20 % (!) in stable atmosphere.
- Given the frequency/number of non-neutral observations that can result in serious error in wind prediction and finally in wind resources estimation.
- Although the problem of is not new, a lot of space for improvement is visible and desired.

Conclusions

References

Uncertainty estimations for offshore wind resource assessment and power verification

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dfousek@gres.gr - mouzakis@gres.gr
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peppas@floatmast.com - papatheodorou@floatmast.com

Scope

• Compare various offshore measurement configurations based on the relevant introduced uncertainty.

• Calculate all the uncertainty components defined in IEC 61400-12-1:2017 for real case scenarios.

Methodology

• Define virtual Power Curve verification cases, based on a NREL 5MW offshore wind turbine, combining its power curve with synthetic data from real onshore campaigns. For each uncertainty component, apply the default recommended values in [1] (or typical ones from similar onshore test campaigns). Statistical uncertainties and the power measurement uncertainties are all assumed common for all five cases.

• Introduce 2 additional uncertainties due to: i) data availability issues and ii) structure motion. Based on published data [3],[4],[5],[6] assume wind speed uncertainty of 1.0% for a campaign with 80% data availability, 1.4% for a floating moving structure and 0.7% for a significantly more stable floating TLP platform.

Table 1: The 5 examined configurations

<table>
<thead>
<tr>
<th>Case</th>
<th>Method</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Fixed permanent full rotor height meteorological mast (ie: 150m)</td>
<td>+ High accuracy &amp; TI measurements (cup/sonic) + High data availability + Rotor equivalent wind speed - Very high installation cost - Significant flow disturbance</td>
</tr>
<tr>
<td>B</td>
<td>Fixed permanent hub height meteorological mast (ie: 90m) with RSD</td>
<td>+ High accuracy &amp; TI measurements (cup/sonic) + High data availability + Rotor equivalent wind speed + RSD continuously verified against cups - Flow disturbance</td>
</tr>
<tr>
<td>C</td>
<td>Fixed permanent below hub height meteorological mast (ie: 40m) with RSD</td>
<td>+ High accuracy &amp; TI measurements (cup/sonic) + High data availability + Rotor equivalent wind speed + RSD continuously verified against cups + High installation cost</td>
</tr>
<tr>
<td>D</td>
<td>RSD on floating vessel (i.e. floating LIDAR)</td>
<td>+ Low installation cost + Rotor equivalent wind speed - No flow disturbance - Lower data availability - Motion affected TI measurements - Strong effects from structure movements</td>
</tr>
<tr>
<td>E</td>
<td>Temporary TLP meteorological mast (ie: 40m) with RSD (i.e.: FloatMast)</td>
<td>+ Good accuracy &amp; TI measurements (cup/sonic) + High data availability + Rotor equivalent wind speed + RSD continuously verified against cups - Low installation cost - Limited effects from structure movements</td>
</tr>
</tbody>
</table>

Wind speed (left) and AEP (right) resulting uncertainties

Conclusions

When strict compliance to IEC 61400-12-1:20017 is unachievable (deep waters, floating wind farms) or requires high financial costs, the proposed methodology introduces two offshore configurations and compares the resulting uncertainties.

References

1. IEC 61400-12-1:2017 Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines
5. Assessment of the Verification for Fugro SEAWATCH floating lidar at Ijmuiden, Technical Note No.: GLGH-4257 13 10378-R-0003, Rev. B
Using a Langevin model for the simulation of environmental conditions in an offshore wind farm

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Introduction

- The optimization of operations and maintenance (O&M) is a focus of current research.
- Many simulation models/optimizations rely on artificially generated weather time series to test different strategies.
- We present a novel approach to modeling both the significant wave height and wind speed based on measurements from the site.
- We use a stochastic process called Langevin process. First, equations are fitted to the available data, which are then used to generate the artificial weather.

Langevin Process

- Deterministic contribution
  \[ F = D^{(3)} \]
- Stochastic contribution
  \[ G = \sqrt{D^{(2)}} \xi \]
- The stochastic contribution makes it easy to include uncertainty.

Data

- ECMWF: re-analysis, 6 hour resolution, Dogger Bank WF, 37 years
- Fino 1: measurements, 30min/10min means, Alpha Ventus, 6 years

Wave height

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.44</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>Simulation</td>
<td>1.51</td>
<td>0.92</td>
</tr>
<tr>
<td>Simulation without seasonal effect</td>
<td>1.44</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Wind speed

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.99</td>
<td>4.66</td>
<td></td>
</tr>
<tr>
<td>Simulation</td>
<td>9.83</td>
<td>4.38</td>
</tr>
<tr>
<td>Simulation without seasonal effect</td>
<td>10.03</td>
<td>4.34</td>
</tr>
</tbody>
</table>

Table: Statistics of the Fino 1 data and the simulations that are based on the data. For the simulation without seasonal effect, one system of equations was fitted for the whole year. In the seasonal simulation, each month was estimated separately.

Conclusions and Future work

- The analysis shows that the Langevin process is an adequate alternative to other weather simulation models.
- The properties of the waves (distribution and persistence) are represented very well.
- Higher sampling frequency in the data improves the model.
- Multidimensional Langevin process might capture the correlation between wave heights and wind speeds is another topic for further research.

Selected References


Fig: The monthly means of significant wave height and wind speed, both for the original data and the simulation based on it. The model was fitted to the re-analysis data from the ECMWF.

Fig: The distribution of wave heights and wind speeds over 6 years. Shown is the data, simulation and simulation without the seasonal effect.

Fig: Persistence of wave heights under 1.5m and wind speeds under 20m/s for two different month for the Fino simulation.
Optimization of monopiles with genetic algorithms

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\textsuperscript{3} Delft University of Technology, Delft, Netherlands

Acknowledgements: Results of this work have been obtained by Matthieu Rhomberg during his master thesis in cooperation with Ramboll, NTNU and TU Delft. Input from several experts from Ramboll is greatly acknowledged. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 642108.

Motivation
Knowledge about the scaling of steel mass of monopiles is needed to decide for which service life an offshore wind farm should be planned. It is impossible to perform computer-aided optimization with aero-hydro-elastic simulations of several thousand of load cases.

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Genetic algorithm
- Minimize monopile mass
- 5 design variables
- Constraints: fatigue damage, weldability, resonance, buckling
- Aero-hydro-elastic load simulations in the time domain with 120 load cases and importance sampling
- Optimization for different design lifetimes: 25, 50, 75, 100 years (DFF=1)

Reduction of load cases with importance sampling
- A cumulative distribution function (CDF) is set up for fatigue damages caused by every load case
- 120 load cases are sampled from the CDF
- Aero-hydro-elasticsimulations are performed for these load cases with ROSAP and LACflex
- Fatigue damages are estimated with importance sampling and a correction factor $f_k$

$$D_{\text{est}} = \frac{1}{n} \sum_{i=1}^{n} D_i \cdot C_L \cdot g_i$$

$$D_{\text{corr}} = f_k \cdot D_{\text{est}}$$

$$f_k = \mu_k + n \cdot \sigma_k$$

How does steel mass increase if monopiles are designed for a longer lifetime?

Research objective
Develop a smart method to reduce the number of require load simulations during the design optimization while keeping the complexity of load and structural analysis at industrial standard.

Case study
8 MW turbine
DLC 1.2 + 6.4
1700 load cases

Importance sampling to reduce number of load cases
- 120 load cases instead of 1700 (93\% reduction)
- Target lifetime of optimization met with only 1-7\% difference
- Fast and accurate method for use in computer-aided optimization

Importance sampling to reduce number of load cases
- 120 load cases instead of 1700 (93\% reduction)
- Target lifetime of optimization met with only 1-7\% difference
- Fast and accurate method for use in computer-aided optimization
Cone penetration data classification by Bayesian inversion with a Hidden Markov model

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1Department of Mathematical Sciences, Norwegian University of Science and Technology, Trondheim, Norway
2Department of Rock and Geotechnical Engineering, SINTEF Building and Infrastructure, Trondheim, Norway

Introduction
The Cone Penetration Test (CPT) is an in-situ test that is frequently applied to estimate subsurface stratigraphy, soil properties, and parameters for a direct geotechnical design [4]. Soil classification from CPT data is commonly based on classification charts with predefined soil classes [6] and [7]. These are often considered no more than as indicative. We investigate the application of the Hidden Markov Model (HMM) to the CPT classification problem.

Model

Notation
Consider a CPT profile with measurements along the grid $Z_d = \{1, \ldots, Z\}$ with $z$ increasing with depth. A vector of CPT measurements is denoted $d_z = [d_{i1}, \ldots, d_{iZ}]$. The actual soil class profile at the location is denoted $\kappa = \{\kappa_1, \ldots, \kappa_Z\}$, where $\kappa_z$ belongs to a set of different soil classes $\Omega_z = \{1, \ldots, K\}$. Note that soil classes can be arbitrarily defined to describe different geological features.

Model definition
We want to calculate the probability of any profile of soil classes given the CPT measurements, $p(\kappa|d)$. In the Bayesian setting, this probability is denoted as posterior because it incorporates the measurements with the additional or prior knowledge. The posterior probability is defined according to the Bayes law as follows $p(\kappa|d) = \frac{p(d|\kappa)p(\kappa)}{p(d)}$, where $p(\kappa)$ is the prior model, $p(d|\kappa)$ is the likelihood model, and $p(d)$ is a normalizing constant. With these two distributions the full posterior is defined as $p(\kappa|d) = \frac{p(d|\kappa)p(\kappa)}{\int p(d|\kappa)p(\kappa)\,d\kappa}$. The evaluation of the normalizing constant, $p(d)$, is usually unstable and most often avoided.

Likelihood model
The likelihood model, $p(d|\kappa)$, provides a statistical model that relates CPT measurements to soil classes. The likelihood model is based on two assumptions, conditional independence between the CPT data vector at each step, $d_z$, given $\kappa$ and single site dependence between $d_z$ and $\kappa$. These two assumptions lead to the following relation:

$$p(d|\kappa) = \prod_{z=1}^{Z} p(d_z|\kappa_z).$$

A Gaussian bivariate likelihood model is selected to model the aforementioned relations. The Gaussian bivariate model requires the assessment of mean parameters and covariance matrices for all classes. These parameters can be estimated by the using the CPT data, $d$, and the actual soil class profile $\kappa$ vector available from calibration boreholes.

Prior model
As the prior for $\kappa$ a first order Markov chain is selected. Denote the probability of transitioning from any soil class $\kappa_{z-1}$ to any soil class $\kappa_z$ as $p(\kappa_z|\kappa_{z-1})$. The $(K \times K)$ matrix $\mathbf{P}$, with $K$ being the number of separate soil classes, outline the probability for all possible transitions. The Markov chain prior is assumed to homogenous. The prior probability of any soil class vector, $\kappa$, is given by the following expression:

$$p(\kappa) = p(\kappa_1) \prod_{z=2}^{Z} p(\kappa_z|\kappa_{z-1}).$$

An estimator $N$ of the transition matrix $\mathbf{P}$ is estimated from observed transformations in known soil profiles. This estimator can be estimated in a strict way, only allowing transitions that are observed, or in a lenient way, allowing transitions from any formation to any deeper laying formation.

Posterior model
Our choices for likelihood and prior models result in a posterior model that is a Hidden Markov Model (HMM) [5]. In an HMM, the states or soil classes of the Markov chain are hidden, but at each step the hidden soil class has a corresponding observation. The structure of the dependences in the HMM is visualized in Figure 1.

We derive the following expression for the posterior model on a first order Markov chain form:

$$p(\kappa|d) = \frac{p(d|\kappa)p(\kappa)}{\int p(d|\kappa)p(\kappa)\,d\kappa}.$$

Note that this posterior Markov chain does not have a stationary transition matrix. Note also that the Gaussian bivariate distributions, defining the likelihood model, are not updated.

Posterior model inference
The recursive Forward-Backward algorithm e.g. [1] is used to calculate the posterior distribution $p(\kappa|d)$ without explicitly calculating the constant $p(d)$. The Forward-Backward algorithm calculates $p(\kappa_z|d_{1:Z})$ for all combinations of $\kappa_z$ and $d_{1:Z}$, and for all values of $\kappa_z$ and $d_{1:Z}$ by fully defining the posterior model $p(\kappa|d)$. From this we can find estimators such as the maximum a posteriori prediction, (MAP), and the marginal maximum a posteriori prediction (MMAP). As well as simulate soil class profiles.

To compute the MAP predictor we implement the application of the Viterbi algorithm, e.g. [2] is needed. This recursive algorithm exploits the Markov property of the posterior model to find the most probable soil class vector. The predictions are compared to the true profiles or if these are not available some other reliable independent prediction. Also a simple Naive Bayesian (NB) predictor is used as base for comparisons. This NB predictor suits this purpose as it does not take spatial correlation into account.

Case study

Geological information
The implemented model is applied to the classification of CPT profiles at the Sheringham Shoal Offshore Wind Farm (SSOWF). The geology at the location is described by six formations e.g. [3], these are in order of increasing depth, Holocene sand (HS), the Botany Cut formation (BC), the Bolders Bank formation (BBD), the Egmond Ground Formation (EF), the Swarte Bank formation (SBK) and the Cretaceous chalk (CK) layers beneath.

Extensive soil investigations was conducted at the SSOWF site, a series of CPT soundings and boreholes in the proximity of some of these sites. We will use one CPT profile and one of the bore hole profiles. Given that the borehole is very close to the CPT profile, it assumed that the borehole soil stratigraphy can be used as the actual soil class profile. This information is necessary both to estimate the prior and the likelihood distributions.

Results
The profiles are coloured with red colours corresponding to clay dominated formations and blue corresponding to sand dominated formations. Deeper colours represent deeper formations. As no measurements are taken when chalk is hit the last formation, CK, is not present in the profiles.

Figure 2: Training CPT profile, non-strict transition matrix: actual soil class profile, model predictions (MAP, MMAP and NB) and marginal probabilities.

The first set of profiles are calculated with a lenient prior matrix while the second set of results are calculated with a strict prior matrix. It is clear that a stricter prior makes sure the ordering stays closer to the observed profiles. With the less strict prior matrix the model tends to mistake formations that are dominated by the same soil characteristics for each other.

Figure 3: Training CPT profile, strict transition matrix: actual soil class profile, model predictions (MAP, MMAP and NB) and marginal probabilities.

Conclusions
This study examined the application of the Hidden Markov Model to the soil classification based on CPT measurements. The model is composed of a Markov chain that models spatial ordering of soil classes along a CPT profile and a Gaussian likelihood model that links CPT measurements with different soil classes. The Bayesian formulation of the model is considered as advantageous for the considered problem as it allows the model to integrate additional sources of information, commonly available in a CPT-based soil classification. Additional advantages, when compared to the CPT classification based on classification charts, include arbitrary definitions of soil classes supported by the Gaussian likelihood model. The probabilistic framework of the model allows it to account from some of the uncertainties in the classification process. The Bayesian setting of the model provides a framework for a more consistent treatment of additional sources of information in the CPT-based soil classification. The model achieved good performance when applied to the classification of CPT profiles from the Sheringham Shoal Offshore Wind Farm. However, additional and more extensive tests are necessary to further validate the model performance. Further extensions of the model are planned to adapt the soil class definitions to data clusters instead of geological formations and to consider Bayesian updating of the relations between soil classes and CPT measurements.

References
The focus of this paper is on the environmental loads and responses of mooring systems for a semi-submersible at water depth of 50 m, 100 m and 200 m. Preliminary design has been carried out to determine mooring line properties, mooring system configurations and document the static performances. A fully coupled time domain dynamic analysis for extreme environmental conditions was performed using Simo-Riflex-AeroDyn. Four different load models were applied in order to check the influence of different load components including the effect of wind, current and second order wave forces by means of Newman’s approximation and a full QTF method.

Mooring design for moderate water depths is relatively easy to achieve, but it is challenging for shallow water. Mooring line tension increases in a nonlinear manner when the offset is large and it is more significant in shallow water.

The highly non-Gaussian responses in shallow water indicates possible extreme mooring line tension and floater motion especially.

Newman’s approximation is good if the frequency difference is small, which is normally the case for horizontal motions for floating structure especially in deep water. Newman’s approximation becomes uncertain when it comes to shallow water. In this paper, Newman’s approximation will be considered in horizontal motions while full QTF method will include contributions from all six degrees of freedom.

Mooring line tension increases nearly linearly when the offset is small, then it increases in a nonlinear manner for all three water depths. The phenomenon becomes more significant when water depth decreases.

Results and discussions

Non-Gaussian response

<table>
<thead>
<tr>
<th>Wave</th>
<th>Wind</th>
<th>Current</th>
<th>Load cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>The wind and wave conditions correspond to 50-year return period and current condition refers to 10-year return period.</td>
</tr>
<tr>
<td>1</td>
<td>Yes</td>
<td>No</td>
<td>U_L_1: 41.86</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Newman</td>
<td>U_L_2: 38.37</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>Full QTF</td>
<td>H_L_1: 13.4</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Full QTF</td>
<td>T_L_1: 1.05</td>
</tr>
</tbody>
</table>

Fully coupled dynamic analysis

Flowchart of the analysis process and software used.

Conclusions

During mooring system design phase, two factors that can influence mooring line tension significantly were mainly considered: geometrical effect and increased stiffness for large offset.

As water depth decreases, the contribution from difference frequency part becomes increasingly more significant. Therefore in order to capture the low-frequency response accurately, a full QTF method is recommended while Newman’s approximation will underestimate the response.

The highly non-Gaussian responses in high sea states indicates possible extreme mooring line tension and floater motion, which makes it quite challenging to design mooring system for extreme environmental conditions especially in shallow water.

Acknowledgement

The first author is financially supported by Chinese Scholarship Council (CSC).

Reference


Flowchart of the analysis process and software used.
Supply chains for floating offshore wind substructures – a TLP example

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FLOATING OFFSHORE WIND

On November 4th 2016 the Paris Agreement on Climate Change came into force. To achieve the goals of this agreement CO₂-emission-free energy production is a key element. Offshore wind power will be a major player in this field. Hence floating offshore wind solutions can provide an economically viable as well as ecologically friendly power source in water depths of 50m and deeper. From 2011 onwards, the University of Rostock has been involved in a floating offshore wind research project together with the company GICON. The GICON-TLP, a TLP substructure fabricated out of pre-stressed concrete elements, has been developed and tested over several years to reach a development stage as an economic and ecological solution. Tests of the final design in operation conditions have been done successfully at the ECN in Nieuwpoort within the course of MarineNet.

Another characteristic of this TLP is the high level of modularity to maximize the feasibility within the supply chain and with suppliers.

SUPPLY CHAIN OPTIMIZATION

- High modularity of the substructure  → The TLP consists only of five main components:
  - Bottom and top nodes, transition piece, buoyancy bodies and pipes

All components can be produced at multiple locations and thus by different suppliers. This leads to cost-saving potential based on the possibility to have a choice of suppliers. Additionally the production capacities of multiple suppliers can be used simultaneously. Since smaller and lighter components will be transported during most of the transport process, logistical boundary conditions can be considered.

OPTIMIZATION THROUGH DEVELOPMENT

2nd Generation GICON-TLP

Throughout the development process, some changes have been made with regard to the optimization of the supply chain and manufacturability of the GICON-TLP. To reduce the costs of the structure, the material has been changed from steel to steel-reinforced ultra-high performance concrete. Additionally the level of modularity of the structure has been increased by replacing the diagonal beams by pipes of the same type as used for the vertical and horizontal connections. This leads to lower costs for the yard as well as a reduced fabrication and installation time.

<table>
<thead>
<tr>
<th>Dimensions [m]</th>
<th>2G72-2.2MW</th>
<th>2G73-5.3MW - Steel</th>
<th>2G73-5.3MW - concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [t]</td>
<td>800</td>
<td>1,800</td>
<td>3,400</td>
</tr>
<tr>
<td>Single heaviest component</td>
<td>Buoyancy Body 130t</td>
<td>Buoyancy Body 310t</td>
<td>Vertical Pipe 80t</td>
</tr>
<tr>
<td>Material</td>
<td>Steel</td>
<td>Steel</td>
<td>Steel-concrete</td>
</tr>
<tr>
<td>Material cost TLP [€/t]</td>
<td>2,500</td>
<td>2,500</td>
<td>450</td>
</tr>
<tr>
<td>Assembling time</td>
<td>4 months</td>
<td>Min. 4 month</td>
<td>4 weeks</td>
</tr>
<tr>
<td>Largest single component</td>
<td>10 m long</td>
<td>14 m long</td>
<td>28 m</td>
</tr>
<tr>
<td>9 m diameter</td>
<td></td>
<td>14 m diameter</td>
<td>3 m diameter</td>
</tr>
</tbody>
</table>

FINAL ASSEMBLY

- The final assembly can be done at a port close to the wind farm.
- All components will be delivered to the assembly side and assembled in four weeks.

POSSIBLE SUPPLY CHAINS IN EUROPE

ACKNOWLEDGMENT

We like to express our sincere gratitude to the German Federal State of Mecklenburg-Vorpommern for the financial support provided to the GICON – Großmann Ingenieur Consult GmbH (Project number: V430-1-260-2012/102).
Critical Review of Floating Support Structures for Offshore Wind Farm Deployment

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Abstract

Current situation: - numerous deep water sites with promising wind potential \textarrow{→} floating structures possible, bottom-fixed systems not;
- large diversity in floater concepts \textarrow{→} fast achievement of high technology readiness levels (TRLs) inhibited.

Thus, different floating support structures are assessed with respect to their suitability for offshore wind farm deployment. Based on a survey, a multi-criteria decision analysis (MCDA) is conducted, using the technique for order preference by similarity to ideal solution (TOPSIS). With the individual scores of ten floater categories, considering the weighting of ten specified criteria, suitable concepts are identified and potential hybrid designs, combining advantages of different solutions, are suggested.

Methodology

Survey: - weights (1: not important - 5: important) represent importance of each criterion with respect to offshore wind farm deployment.
- scores (1: least applicable - 5: most applicable) assigned for each criterion to each alternative;
Results

Survey: - fast achievement of high technology readiness levels (TRLs) inhibited.

Table 1: Weights, scores, ranks

| Weight | Score | Rank | TRL | Description (based on Horizon 2020 https://ec.europa.eu/)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>4.26</td>
<td>1.</td>
<td>(0)</td>
<td>idea for an unproven concept</td>
</tr>
<tr>
<td>II.</td>
<td>3.43</td>
<td>11.</td>
<td>1</td>
<td>basic principles observed</td>
</tr>
<tr>
<td>III.</td>
<td>2.91</td>
<td>35.</td>
<td>2</td>
<td>technology concept formulated</td>
</tr>
<tr>
<td>IV.</td>
<td>3.24</td>
<td>5.</td>
<td>3</td>
<td>experimental proof of concept</td>
</tr>
<tr>
<td>V.</td>
<td>2.33</td>
<td>98.</td>
<td>4</td>
<td>validation in lab</td>
</tr>
<tr>
<td>VI.</td>
<td>3.40</td>
<td>3.</td>
<td>5</td>
<td>validation in relevant environment</td>
</tr>
<tr>
<td>VII.</td>
<td>3.38</td>
<td>7.</td>
<td>6</td>
<td>demonstration in relevant environment</td>
</tr>
<tr>
<td>VIII.</td>
<td>3.59</td>
<td>3.</td>
<td>7</td>
<td>demonstration in operational environment</td>
</tr>
<tr>
<td>IX.</td>
<td>3.02</td>
<td>9.</td>
<td>8</td>
<td>system complete and qualified</td>
</tr>
<tr>
<td>X.</td>
<td>3.10</td>
<td>2</td>
<td>9</td>
<td>proven in operational environment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TRL</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>II</td>
<td>II</td>
</tr>
<tr>
<td>III</td>
<td>III</td>
</tr>
<tr>
<td>IV</td>
<td>IV</td>
</tr>
<tr>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>VI</td>
<td>VI</td>
</tr>
<tr>
<td>VII</td>
<td>VII</td>
</tr>
<tr>
<td>VIII</td>
<td>VIII</td>
</tr>
<tr>
<td>IX</td>
<td>IX</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Conclusions

- Assessment of ten floating wind turbine support structures wrt ten criteria focusing on wind farm deployment;
- MCDA based on survey results and TOPSIS method;
- Costs are still most important and advanced spars have the highest potential to develop for multi-MW wind farm deployment.
Assessment of the state-of-the-art ULS design procedure for offshore wind turbine sub-structures

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Abstract

Sub-structures of offshore wind turbines are designed according to several design load cases (DLCs). These DLCs are given in the current standards, and are supposed, on the one hand, to cover accurately all significant load conditions to guarantee reliability. On the other hand, they should include only necessary conditions. Here, for ULS conditions, the question whether the current design practice is, firstly, sufficient, and secondly, sensible concerning the computing time by only including necessary DLCs is addressed. Probabilistic simulation data of five years of normal operation is used to extrapolate 20-year ULS loads (comparable to a probabilistic version of DLC 1.1 for sub-structures). These ULS values are compared to several deterministic DLCs required by current standards (e.g. DLC 6.1). Results show that probabilistic, extrapolated ULS values can exceed standard DLC loads. Hence, the current design practice might not always be conservative. Especially, the benefit of an additional DLC for wave peak periods close to the eigenfrequency of the sub-structure is indicated.

Simulation setup

For all time domain simulations, the FAST6 code is used. A soil model applying soil-structure interaction matrices enhances the FAST6 code [1]. The NREL 5MW reference turbine with the OSC monopile is investigated.

For the probabilistic approach, statistical distributions for environmental conditions were derived using the FINC3 data (North Sea) [2]. For the DLC-based approach, extreme values are derived here using the same data.

For the ULS analysis several limit states, including the plastic limit state and the buckling limit state for the monopile, are used to calculate utilization factors (UFs). Additionally, ULS proofs for the foundation piles are performed according to GEO2. Aging effects etc. are not taken into account.

ULS calculation

DLC-based approach

The DLC-based approach uses extreme environmental conditions, e.g. the 50-year storm. Hence, extreme values are derived using 4-week maxima that are directly extracted from the data. Fig. 1 illustrates this process for DLC 6.1: 4-week maxima are extracted for the wind speed, but for the turbulence intensity only the corresponding values are used. These values are not the maxima, as the highest turbulence does not coincide with extreme wind speeds. Statistical distributions are fitted to the 4-week maxima (or there corresponding values) using a maximum likelihood estimation (MLE). Having determined a statistical distribution, the values corresponding to a recurrence period of 50 years can be determined (see Fig. 1).

Probabilistic approach

A possible addition to the deterministic DLC-based approach that takes scattering conditions into account is a probabilistic or Monte Carlo simulation approach. Environmental conditions are sampled according to their depending distributions to enable a simulation of 5 years of realistic lifetime (~250000 samples) including un favourable, but realistic parameter combinations. An extrapolation to 20 years of operation is possible by fitting distributions to the extracted peaks (maxima of all simulations). For the fit, an MLE and only the highest utilisation factors (tail fitting) are used.

Results

In Fig. 3, the DLC-based approach is compared to the probabilistic one. For the DLCs, mean and maximum values (error bars) of 100 DLC simulations are shown. For the probabilistic approach, 1-year, 5-year, and 20-year values are displayed. The 5-year value is the maximum UF of all simulations, while 1 and 20-year values are based on bootstrap samples (and an extrapolation for the 20-year value). The probabilistic approach leads to the highest ULS loads. As these loads exceed the ULS values of the DLC-based approach for the 5-year value, this fact is independent of the extrapolation technique. Most of the extreme UFs occur at wave periods of around 4s being close to the resonance frequency of the monopile. Hence, the probabilistic approach reveals the fact that wave resonance might be a problem for monopiles with larger diameters. Wave resonance is not covered sufficiently by the DLC-based approach, as deterministic wave periods are assumed.

Conclusion and Outlook

Results show that independent of the load extrapolation technique - probabilistic, extrapolated ULS values can exceed the deterministic 50-year ULS loads of the standard DLCs. Therefore, for sub-structures, the current DLCs (excluding fault cases etc.) might not always be conservative. The extrapolation of loads in power production can lead to higher loads, if a probabilistic approach is applied. In the long term, a reconsideration of DLCs might be valuable. Some load cases can perhaps be removed; others, like a DLC for wave resonance problems, might be missing. Still, due to the imitation of this work to simplified models (FAST6), sub-structures, no fault cases etc. an exclusion of DLCs based on this work would be premature.

References


Fig. 2: UFs of all probabilistic simulations (5 years): lognormal tail fit for 20-year extrapolation

Fig. 3: Left: Comparison of UFs; Right: Investigation of high UFs for the probabilistic approach

Fig. 1: Top: Wind speed and TI data of 24 weeks. 4-week periods and selected peaks are marked. Bottom: Extrapolation of 5-year wind speeds and the corresponding turbulence.

Abstract

This study covers an experimental analysis of the pressure levels recorded on the heave plates of a new concept of floating platform — SATH — developed by Saitec Offshore Technologies during some wave tank tests performed in the facilities of IHCantabria, in Santander (Spain).

The pressure field was recorded on the center of the top and bottom faces of the bow heave plate. The data analyzed was the significant pressure difference, which will cause a net force on the structural components (see pressure peaks identification, Fig 6).

When the pressure magnitudes (and the difference —or net— pressure) on the faces of the plates were graphed against the ratio of incident wave period $T_w$ to the natural period in heave $T_n$, some clear trends could be identified (see images in Fig 7).

It was noticed that the evolution of the plate pressures had a similar shape to that of the normal accelerations. This can be graphically shown, too, with the correlation between the average peak magnitudes of these two variables, as in Fig 8:

The Pearson’s r coefficient for the normalized pressure difference and the plate’s normal acceleration turned out to be $r > 0.93$, indicating an important correlation between these two magnitudes.

This is coherent with the idea that a normal acceleration in the heave plate will tend to drag (accelerate) fluid with it (added mass phenomenon), causing a net force on it.

Method and data acquisition

The experimental data included 25 series of monochromatic waves of different wave heights and amplitudes, in a deep water environment, which were used in the data collection for this study.

Data acquisition: two custom-made submerged pressure transducers —Honeywell 40PC series—, with a pressure range of 0-15 psi were used to measure the dynamic pressure (meaning all pressure components not included in the static pressure as measured before the test began). Sampling frequency on these transducers was 50 Hz.

In every time series, the transient part was disregarded and the peaks identified in the stationary signal.

For motion tracking, a Qualisys system was used, with a set of 4 infrared cameras and a sampling frequency of 100 Hz.

The time series of the acceleration at the center of the bow heave plate was computed by combining those in heave, pitch and surge (see in the equation that follows —rigid body mechanics—). The peaks identified in these series were then compared to the magnitude of the pressure for the corresponding regular wave ($H_T, T$) that caused them.

In the following equation, $a_y$ is the plate acceleration, and is computed from the linear acceleration on surge ($a_x$) and heave ($a_z$). The regular acceleration in pitch ($a_p$) also causes an acceleration on the plate proportional to the lever arm $r$.

$$a_y = (a_x + r) \sin \theta + (a_z - r) \cos \theta$$

Examples of the correlation of the net pressure and the plate’s normal acceleration are shown in Fig 9 for two different test conditions.

Results

The pressure field was recorded in the transducers on the center of the top and bottom faces of the bow heave plate. The data analyzed was the significant pressure difference, which will cause a net force on the structural components (see pressure peaks identification, Fig 6).

When the pressure magnitudes (and the difference —or net— pressure) on the faces of the plates were graphed against the ratio of incident wave period $T_w$ to the natural period in heave $T_n$, some clear trends could be identified (see images in Fig 7).

It was noticed that the evolution of the plate pressures had a similar shape to that of the normal accelerations. This can be graphically shown, too, with the correlation between the average peak magnitudes of these two variables, as in Fig 8:

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This is coherent with the idea that a normal acceleration in the heave plate will tend to drag (accelerate) fluid with it (added mass phenomenon), causing a net force on it.

Conclusions

The work presented here was originally performed as part of a Master’s Thesis for KTH Royal Institute of Technology (Stockholm). Great thanks to the main supervisor, Prof. Karoumi, for his help and advice during the research.

I wish to thank as well the IHCantabria and their staff, who worked hard to successfully perform the tests in their facilities and who kindly agreed to share the raw data for further analyses, such as this one.

References


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I wish to thank as well the IHCantabria and their staff, who worked hard to successfully perform the tests in their facilities and who kindly agreed to share the raw data for further analyses, such as this one.

Contact info

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State-of-the-art model for the LIFES50+ OO-Star Wind Floater Semi 10MW floating wind turbine

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Introduction

A FAST [1] model of the DTU 10MW Reference Wind Turbine [2] mounted on the LIFES50+ OO-Star Wind Floater Semi 10MW platform [3] has been developed from a FAST model of the onshore turbine [4]. The changes entail controller, tower structural properties, platform hydrodynamics and mooring system. The basic DTU Wind Energy controller was tuned to avoid the negative damping problem. The flexible tower was extended down to the still water level to capture some of the platform flexibility. Hydrodynamics were precomputed in WAMIT, while viscous drag effects are captured in HydroDyn by the Morison drag term. The platform was defined in HydroDyn to approximate the main drag loads on the structure, keeping in mind that only circular members can be modelled. The mooring system was implemented in MoorDyn. A set of simulations was carried out to assess the system natural frequencies, the response to regular waves, the controller behavior and the global system response to stochastic wind and waves. Further details on the modelling approaches, the simulation results and the model availability can be found in [5].

Modelling of the tower

To capture some of the floater flexibility, the portion of floating platform between SWL and tower interface was modelled as part of the tower, and the inertia properties of the platform were modified accordingly. This approach reduced the tower coupled natural frequency from 0.786 Hz to 0.75 Hz. However, the tower natural frequency obtained with a fully flexible numerical model was 0.59 Hz. This difference highlights the effect of the flexible substructure on the dynamics of the system.

Modelling of the viscous drag

Given the complexity of the floating platform, the viscous drag loads on the physical structure (left) were modelled in HydroDyn with a series of cylindrical members and heave plates (right). This ensures that the global drag loads in surge, heave and pitch are well captured.

The object of study

DTU 10MW Reference Wind Turbine + OO-Star Wind Floater Semi 10MW

Response to stochastic wind and waves

The system’s response to small irregular waves and near-rated turbulent wind is shown here. The platform responses are excited by wind (surge, pitch) and waves (heave, nacelle). The tower natural frequency is also excited. The controller can be seen in action around 5200 s, when the rotor exceeds the rated speed and the blades are pitched to return the wind turbine to below-rated conditions.

Literature cited

https://nwtc.nrel.gov/FAST8

Acknowledgments

This work is part of the project LIFES50+. The research leading to these results has received funding from the European Union Horizon2020 programme under the agreement H2020-LCE-2014-1-640741.
Introduction
Development of offshore wind farms at intermediate depths rely on the efficient design of floating platforms. While their motion response in wind and waves is often well predicted by the established aero-hydro-elastic models, the forcing from nonlinear waves, viscous damping effects and green-water events require higher fidelity modelling such as fully coupled computational fluid dynamics (CFD) simulations. In this paper, we present the numerical setup and validation of a two-phase CFD solver for the LIFES50+ OO-Star Wind Floater Semi 10 MW, hereafter called OO-Star floater for brevity. The floater has been selected by the LIFES50+ [1] project for extended numerical modelling and physical model tests.

Numerical set up
The open source toolbox, OpenFOAM [2] is employed and a moving mesh technique is used to account for floating body motions in waves. The grid is generated and refined by importing the geometry and using the unstructured meshing library, snappyHexMesh. For this presentation, first order Stokes waves are generated with the waves2Foam wave generation toolbox [3] and by use of a relaxation zone approach on the far-field. Figure 1 shows a snapshot of the numerical domain and the floater and the corresponding dimensions.

Results – Floater’s hydrodynamic coefficients
Response of the floater to forced surge and heave motions in calm water are analysed to obtain added mass and damping coefficients:

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Draft [m]</th>
<th>Freeboard [m]</th>
<th>Displ. volume [m³]</th>
<th>Platform mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semisubmersible</td>
<td>Post-tensioned concrete</td>
<td>22.00</td>
<td>11.0</td>
<td>2.3509E+04</td>
<td>2.1709E+07</td>
</tr>
</tbody>
</table>

Results – Wave excitation forces on the fixed floater
Three incident waves of steepness ratios from 0.05 to 0.35 are simulated:

References
[1] Pegalajar-Jurado, A; Borg, M.; Bredmose, H., Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m, LIFES50+ Deliverable, project 640741.

Acknowledgments
This work is part of the project LIFES50+. The research leading to these results has received funding from the European Union Horizon2020 programme under the agreement H2020-LCE-2014-1-640741.
INTRODUCTION
Floating Wind Turbine (FWT) prototypes and pilot farms are located in shallower zones than most of the studies in the literature about moored FWT.

- For water depth > 150m, studies have been successful in designing a conventional catenary mooring system with heavy chains.
- For shallower water depth, solutions like taut or semi-taut configurations using material elasticity of synthetic ropes could be attractive for Marine renewable energy devices [1].

Design and comparisons of conventional catenary mooring chain systems and Taut mooring systems using synthetic fibres are done at 65m.

Comparisons in terms of Key Performance Indicators

- Importance of mooring modelling hypotheses for line tensions and floater horizontal motions.

 METHODOLOGY

Key Performance Indicators (KPI)
- CAPEX
- Procurement Cost
- Installation Cost
- Operation And Maintenance (OAM)
- Preventive maintenance
- Heavy maintenance
- Environmental Impact and risk (EI)
- Footprint on seabed
- Touchdown point excursion
- Station keeping performance
- Maximum floater excursion

Design Methodology
Mooring configurations defined parametrically covering design space

- Several Checks for each mooring configuration:
  - Admissible Draft in static position
  - Admissible eigen periods at steady positions
  - Tension criteria according to DNV – OS – J103

Static → Frequency Domain → Time Domain

Reduced number of Design Load cases (DLC) with operating and parked wind turbine cases.

Table 1: Limited number of Design Load Cases

<table>
<thead>
<tr>
<th>DLC</th>
<th>Dir. (°)</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
<th>Uc (m/s)</th>
<th>Uw (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLC 1</td>
<td>247.5</td>
<td>11</td>
<td>15</td>
<td>0.7</td>
<td>44</td>
</tr>
<tr>
<td>DLC 2</td>
<td>247.5</td>
<td>7</td>
<td>15</td>
<td>0.6</td>
<td>44</td>
</tr>
<tr>
<td>DLC 3</td>
<td>247.5</td>
<td>11</td>
<td>15</td>
<td>0.3</td>
<td>11.4</td>
</tr>
<tr>
<td>DLC 4</td>
<td>247.5</td>
<td>7</td>
<td>15</td>
<td>0.2</td>
<td>11.4</td>
</tr>
</tbody>
</table>

KPI Preliminary Evaluation

- CAPEX details
- CAPEX vs Offset Max

CONCLUSIONS
The main outcomes can be summarized by:

a) Different wave directions could significantly change loads in the mooring lines
b) A synthetic methodology with Key Performance Indicators has been defined
c) When taking into account not only CAPEX but also Environmental impact and Station keeping performance, Taut mooring configurations appear efficient.
d) Actual uncertainties on Marine Growth properties on site lead to a certain level of risk and unadapted mooring system.

REFERENCES

Acknowledgment
Y. Perignon from LHEEA is gratefully acknowledged for guidelines and scripts for wave data analysis. The STATIONIS project has been partly funded by BPIFrance, region Pays de la Loire, Vaucluse department, la Metropole Aix-Marseille Provence, la region PACA laureate of 19th call for project FUI
**CONSTRUCTION POSSIBILITIES FOR MONOLITHIC CONCRETE SPAR BUOY SERIAL PRODUCTION**

CLIMENT MOLINS, ADRIÁN YAGÜE, PAU TRUBAT

### SPECIFIC RECOMMENDATIONS

- Around-the-clock pouring of concrete
- Use self-propelled formwork systems that slide on temporary service tracks and with the ability to retract-collapse
- Prioritize use of commercial products from the tunnel industry
- Use vibrating form panels
- Mechanize form erecting, stripping, cleaning and treating
- Use inner concreting train(s)
- Use inner concreting train(s)
- Use self-propelled devices for removal of inner forms
- Use experience from pipe jacking
- Use vibrating form panels
- Around-the-clock pouring of concrete
- High-production speed
- High-jacking forces on form panels

### REQUIREMENTS

- Watertight structure of excellent quality
- Durable water-hastily influences conditions
- Cost-efficient construction
- Post-recovering equipment
- Minimal handling of finished structure
- Smooth transitions in construction transport

### CONCRETE PLACEMENT SCHEMES

**Horizontal**

- Concrete poured radially
- Concrete poured axially

**Vertical**

- Concrete placed through hoists

### GENERAL RECOMMENDATIONS

- Ensure continuous supply of concrete
- Use steel standard form panels
- Back-up equipment and quick response plan in the event of failure
- High-rate placement systems (>100 m³/h)

### CONCRETE CROWN

- Ideal way of filling forms
- Difficult and time consuming

### ARCH-TRAVELLERS

- High-specialized travelers that move on rails parallel to the structure on both sides, they lower forms in place with a pulley system and then release them. A carriage supporting concrete equipment then follows while the Arch travelers are fed new forms and move on to the next section to erect. Different carriages should slide on separate rails to avoid interference between equipment

### ARCH-TRAVELLERS

- High-throughput
- Technological simplicity
- Low execution risk
- Large up-front costs to manufacture massive mold
- Permanency of facilities

### VERTICAL

- Unusual handling
- Vertical displacing

### GIANT RE-USABLE MOLD

- Designed and build traveler
- Quick delivery
- Optimized form handling
- Large up-front costs to design and build traveler

---

**References**


---

**Concrete Placing Schemes:**

- Radial pouring
- Axial pouring
Extreme Response Estimation of Offshore Wind Turbines with an Extended Contour-line Method

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Introduction
A method for long term extreme value analysis of a system with multiple sub-populations of dynamic response characteristics is presented. Offshore wind turbines have, simply formulated, two dynamic response models: one for operating turbine, and one for an idle or parked turbine. Depending on the response of interest, both sub-populations may be important to consider in FLS and ULS design. The present work investigates whether such an approach is feasible on a large monopile-supported offshore wind turbine for extreme response analysis. The long term extreme values are to be found with environmental contours for parked and operational turbines, and verified with an extreme value distribution based on a full long term analysis (FLTA). The work is inspired by [1].

Basic Concept
For each operational sub-population, the extreme response functions are evaluated separately, and later combined into a total extreme response. Let $X_{ia}$ denote the $i$-th extreme response of a given parameter, and $F_{X_{ia}}$ is its cumulative distribution and $G_{X_{ia}}$ is the complementary CDF (CCDF). The total response CCDF is simply found by a weighted sum of the contributing subpopulations:

$$G_{X_{ia}}(x) = \sum_{i} p_{i} \cdot G_{X_{ia}}^{j}(x)$$

where $p_{i}$ is the probability of sub-population $i$. The CDF conditioned on response sub-population $i$ can be evaluated numerically with an FLTA, or with a contour-line approach [2]. The objective is to extend the latter for use with offshore wind turbines, which is done with an alternative approach in [3].

Models
The environmental parameters to be considered are the wind speed $V$, significant wave height $H_s$ and peak period $T_p$. The total extreme response is found in the wind direction $D$ and the wave direction $V$. The wind turbine is exposed to a range of wind directions, and the dynamic response model accounts for the response in all wind directions. The response of the wind turbine is calculated in the form of an equivalent static load, which is then used to calculate the time history of the response. The load is then used to determine the failure probability of the wind turbine.

Results and discussion
In Fig. 5, a characteristic curve is fitted to the response of the wind turbine for the given environmental conditions. The curve is fitted to the data points and is used to estimate the failure probability of the wind turbine. The curve is then used to estimate the failure probability of the wind turbine for the given environmental conditions.

References

Acknowledgements
This work has been carried out at the Centre for Autonomous Marine Operations and Systems (NTNU AMOS). The Norwegian Research Council is acknowledged as the main sponsor of NTNU AMOS. This work is supported by the Research Council of Norway through the Centre of Excellence funding scheme, Project number 225241 • NTNU AMOS.
Floating Offshore Wind Fabrication and Installation of OO-Star Wind Floater

Simen Kleven Rasmussen, Dr.techn.Olav Olsen AS
Hikken Andersen, Dr.techn.Olav Olsen AS
Trond Landba, Dr.techn.Olav Olsen AS

Objective and scope

The key objectives of the paper, for the OO-Star Wind Floater, is to describe:

- A viable and sustainable execution model for floating offshore wind
- A way to reduce cost of energy
- A method with acceptable technical and commercial risk
- A model with flexible solution to future larger wind turbines
- A supply chain for floating offshore wind as an understandable long-term business model

The objective of the presentation is to describe a cost effective floating turbine, the OO-Star Wind Floater, and a viable and understandable execution model for floating offshore wind as a competitive cost of energy, and with an acceptable technical and commercial risk. It is particularly important to show an execution model which is feasible for future large wind turbines. This will help developers and large contractors to understand how a supply chain for floating offshore wind can be developed as a part of an understandable long-term business model.

Introduction

The execution model is based on a robust and cost effective floating solution, the 10 MW DD Star Wind Floater semi-submersible designed by Dr.techn.Olav Olsen AS during the first Phase of the Indian Open Ocean project. The DD Star Wind Floater is a very robust with regard to the following parameters:

- Wind turbine size and weight
- Environmental condition
- Water depth available during assembly, tow, installation and operation
- Design life and durability
- Accidental scenarios
- Local industry, availability

Fabrication and Installation features:

- Fabrication offshore
- Assembly at port prior to being assembled
- Lifting of RAH by offshore crane
- No relative motion between crane and offshore lift during lift and maneuvering
- No need for complicated ballasting operations during lifting
- Completed and tested in port
- Travel fully assembled to the offshore site
- Connected to pre-installed mooring and power cable

Ambition

Floating wind has some significant advantages over bottom fixed. One is to extend the application of offshore wind farms to water depths beyond bottom fixed. 70-80 percent of the world’s wind resource are in areas suitable for floating wind. Floating offshore wind could be a very competitive way of reducing the cost of energy. Floating offshore wind could be a very competitive way of reducing the cost of energy. Floating offshore wind would be a significant market for offshore wind. Floating offshore wind will bring new opportunities for offshore wind.

Computing with bottom fixed wind turbines can only be done through cost reductions, and previous studies point to manufacturing cost as the most influencing design parameter on the LCOE [1].

Floating offshore wind can be standardised beyond bottom fixed offshore wind due to less dependency on water depths and tidal conditions. This will in the long term help to reduce fabrication cost for floating wind and make it competitive with respect to bottom fixed solutions. Considering the large energy potential related to floating offshore wind, and the fact that many countries and regions do not have suitable shallow water areas for bottom fixed developments, the future demand for floating offshore wind is expected to be high.

Another advantage for floating solutions, like the OO-Star Wind Floater, is the ability to do its assembly and testing in a safe and efficient way, even during offshore wind. Elimination of offshore human lift operations is a great benefit and cannot be achieved for bottom fixed wind turbines without large investments in the onshore stability during the installation process. These arguments will only strengthen the future demand for offshore wind and no existing installation techniques for offshore installations. What little there will be a great deal in the market between bottom fixed wind turbines and floating offshore wind. The market will be dominated by bottom fixed wind turbines, while floating offshore wind will gain a similar split between land based wind and offshore wind, where land based wind turbines are smaller than offshore turbines due to transport and handling limitations.

General overview

Below is a typical layout for a construction site, where to deliver 25 complete wind turbines each year. Based on parallel operations, and dedicated construction structures.

- Stations 1: Pre-fabrication of pontoon parts (one month)
- Stations 2: Connection and completion of pontoon parts, including post tensioning (one month)
- Stations 3: Slip forming of corner column and center shaft, and installation of structural elements (one month and mechanical commissioning)
- Stations 4: Controlled launch to sea from slipway cradle or shiplift

- Finalisation: Assembly of tower and RAN, commissioning and testing (five weeks)

1. Pre-fabrication of pontoon parts
2. Connection and completion of pontoon parts
3. Slip forming of corner column and center shaft
4. Controlled launch to sea from slipway cradle or shiplift

Pentagon Fabrication and Assembly

Stations 3: The pontoon parts will be pre-fabricated, so four 18 independent pieces. Construction will be parallel with other operations. The parts will be transported to the slipway site on multi-modules. Skidding lines are accessible for multi-modules from below ground access. Typical construction time is one month for four pieces.

1. Pre-fabrication of pontoon parts
2. Connection and completion of pontoon parts
3. Slip forming of corner column and center shaft
4. Controlled launch to sea from slipway cradle or shiplift

Tower and RAN operations

Two possible ways of handling tower and RAN is proposed:

1. Assembly of tower and RAN is loaded for a robust and cost effective execution model. Our concept operates offshore using 16 RAN, and use of floating cross beams in general. As one RAN can be loaded and lifted out of the tower, the tower will be divided into two sections. The upper part of the tower will be loaded and the substructure will be loaded in small parts to the lower part. The land based crane Nicola will be used for the assembly operations.

2. For future large floating wind turbines the tower and RAN may be assembled on a steel cradle, resting on multi-modules. The cradle, with completely assembled tower, can be moved and skidded into a support frame with a point point close to the gypo.

The substructure is toed into position, and ground by ballasting supports to eliminate the tower wind turbines. The substructure will be fixed to the sea floor, and then loaded into the tower. The complete floating WTS is then ready for testing and subsequent tow to site and installation onto pre-installed mooring system.

Conclusion

The division of construction into stages and parallel production lines allows for an industrialised fabrication process, easy to control and standardised. In addition, the construction of the different parts is an efficient process for fabrication of a large number of units, while cost of establishing the construction facilities will be compensated with the total saving on cost and time.

Floating wind will support bottom fixed solutions for larger turbines (5-25 MW). EWSA acknowledges that a 20 MW turbine is possible with existing materials [2].

DD-Star Wind Floater - benefits:

- Favourable motion characteristics - robust and durable substructure - maintenance cost - large design volume
- Modular construction
- Shuttle minimum draft, full assembly and testing at quayside
- Limited use of heavy lift equipment, no offshore lifts
- Ship change in tower and RAN handling

Pressure interface benefits:

- Division of the pontoon parts reduces the number of skidding lines needed to maintain the production schedule, by looking part of the construction outside the assembly line.
- Construction in stages allows for an industrialised fabrication process, easy to control and standardisable.
- Skidding systems avoiding the use of large, specialized and expensive cranes
- Construction of the units is overlapped, for a better utilisation of the resources and improved construction time

Prior to tower precommissioning due to the existing pieces will be adequately connected and prepared for the post commissioning. The clearance in the crane rail will be measured and ground when the cranes and pontoon joints have reached sufficient compressive strength, typically 1-2 weeks after casting. The needed in the sea is to be trained when pontoon walls are cast. The top deck teak will be tensioned after slip forming of the first part of the central shaft and corner columns.

Estimated time for completing the star pontoon at Station 2 including enough curing time before skidding, is typically 1 month.

There is no need for specialized vessels with long reach cranes. The method is very robust. winter, future large WTS.

The "telescopic ladder" system described is based on a patent owned by Dr.techn.Olav Olsen AS. The method will require that turbine manufacturers modify their design and allow for horizontal assembly. Until this is placed in the end-cradle method will be used.

References

1. SS15H - Technical Data
2. UPiWind - Design limits and solutions for very large wind turbines (EMRAS)
Experimental validation of analytical wake and downstream turbine performance modelling

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MOTIVATION

\begin{itemize}
\item Wake effects in wind farms can cause significant power losses (up to 20\%)
\item Wind farm layout and control optimization can be applied to reduce losses
\item Accurate, simple and fast tools to predict the wake flow are needed
\item Comparison of wake models and small-scale turbine wind tunnel measurements to determine the most accurate wake model
\end{itemize}

EXPERIMENTAL SETUP

\begin{itemize}
\item Wind tunnel measurements at NTNU wind tunnel with a test section of 1.8m (height) x 2.7m (width) x 12.0m (length)
\item Experiment 1: Wake measurements
  \begin{itemize}
  \item Wake measurements behind small scale turbine (D=0.45m) at
  \item Ambient turbulence intensities $I_u = 0.23\%$, 10\%
  \item Upstream turbine pitch angles $\beta = 0^\circ$, 2\°, 5\°
  \end{itemize}
\item Experiment 2: Performance measurements
  \begin{itemize}
  \item Performance measurements of a two aligned small-scale turbines (D=0.90m)
  \end{itemize}
\end{itemize}

MODELLING METHODS

\begin{itemize}
\item Applied wake models:
  \begin{itemize}
  \item Jensen
  \item Frandsen
  \item Ishihara
  \item Bastankah & Porte Agel
  \item Jensen-Gaussian Wake model (JGWM) \cite{3}
  \end{itemize}
\item Adjustment of JGWM: Combination with Crespo and Hernandez turbulence model
\item Application of wind tunnel blockage effect correction \cite{2}
\item Blade Element Momentum method with guaranteed convergence for performance modelling
\end{itemize}

RESULTS

\begin{itemize}
\item Wake Modelling
  \begin{itemize}
  \item Applied wake models:
    \begin{itemize}
    \item Jensen
    \item Frandsen
    \item Ishihara
    \item Bastankah & Porte Agel
    \item Jensen-Gaussian Wake model (JGWM) \cite{3}
    \end{itemize}
  \item Adjustment of JGWM: Combination with Crespo and Hernandez turbulence model
  \item Application of wind tunnel blockage effect correction \cite{2}
  \item Blade Element Momentum method with guaranteed convergence for performance modelling
  \end{itemize}
\item Performance Modelling
  \begin{itemize}
  \item Average prediction error at design tip speed ratio amounts 6.8\%
  \end{itemize}
\end{itemize}

CONCLUSIONS

\begin{itemize}
\item An improvement of the Jensen-Gaussian Wake Model was proposed
\item The adjusted Wake Model was found to give the most accurate wake flow prediction at all test cases
\item Wake Model application on downstream turbine performance modelling resulted in a reasonable performance prediction
\end{itemize}

REFERENCES

Reduced Order Modeling of lift characteristics of NACA0015 using van der Pol equation

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INTRODUCTION
The ability to accurately predict vortex shedding around wind turbine blades is paramount, particularly at high Reynolds number. We employed RANS approach with the use of three turbulence models (Spalart-Allmaras, k-ε and k-ω Shear Stress Transport model) to investigate the vortex shedding pattern on a NACA0015 airfoil. Spectral analysis is performed over the time history of aerodynamic coefficients to identify the dominant frequencies along with their even and odd harmonics. A reduced-order model based on van der Pol equation is proposed for the aerodynamic lift calculation. The model is also tested in a predictive setting, and the results are compared against the full order model solution.

METHODOLOGY
A multiblock approach has been adapted to allow more control over the generation of computational mesh. Quality orthogonal cells are clustered due to the presence of sharp gradients arising from the rapid changes in the flow physics on the surface and the wake region of the airfoil.

RESULTS AND DISCUSSION
Spectral analysis is performed on the time series of the aerodynamic lift coefficient to extract the dominant frequencies. A strong quadratic and cubic couplings is observed in the frequency harmonics. The magnitude of the fundamental frequency at aoa 17 is 0.9 and 1.5 for k-ε and k-ω SST models respectively. The second harmonic is exhibited at the quadratic frequency of 1.8 and 3.0 (f₁ + f₁ = 2 f₁), whereas cubic coupling of the frequency is seen at 3 f₁. Both models have shown distinct magnitudes and peaks for the fundamental frequency and its quadratic and cubic couplings.

CONCLUSION
• Flow separation and vortex shedding pattern of NACA0015 is investigated at high Reynolds number over different angles of attack.
• Spalart-Allmaras, k-ε, k-ω Shear Stress Transport model turbulence models are investigated in two and three-dimensional spatial setting.
• Spectral analysis results show the even and odd frequencies harmonics in the temporal coefficients.
• A reduced-order model (ROM) of lift based on van der Pol equation is proposed.
• ROM model is tested in a predictive setting, and the results are compared against the full order model solution.
Fast divergence-conforming reduced order models for flow

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**Problem:** Repetitive solutions of parametrized flow problems (see left) can be quite demanding, each solution involving up to $10^5-10^9$ degrees of freedom and hours or days of computational time.

**Answer:** Reduced Order Modelling (ROM) offers solutions with lower accuracy but dramatic speedups. When tied to a divergence-conforming high-fidelity method, the gains can be even greater.

**Problem specifics**

High fidelity simulations of stationary Navier-Stokes were performed of flow around a NACA0015 airfoil with chord length of 1 m. The inflow velocity $u_\infty$ varied from 1 to 20 m/s, and the angle of attack $\varphi$ varied from $-35$ to $35^\circ$. The viscosity was fixed at $1/36$.

Snapshots were evaluated at the $15 \times 15$ Gauss points on the parameter domain, and reduced models created with $N = 10, 20, \ldots, 50$ degrees of freedom.

**First four velocity modes**

**First four suprimerizer modes**

**First four pressure modes**

The system matrix (size $2N$) will usually have a rank-deficient velocity-pressure block (VP, indicated with dashed lines). Enriching the velocity space with so-called suprimerizers ensures a full-rank system matrix with size $3N$. A divergence-conforming method will produce a fully divergence-free basis, so the VP-block vanishes, giving a block-triangular system, solvable as two size-$N$ systems instead of one size-$3N$ system.

**Error as a function of speed**

**Discussion**

- ROMs are able to deliver results within two to three orders of magnitude at dramatic speedups.
- Divergence-conforming ROMs can deliver higher speeds, up to one order of magnitude faster in the present examples, by exploiting specific properties of the velocity bases.
Sensitivity analysis of the dynamic response of a floating wind turbine

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Geophysical Institute, University of Bergen

Introduction

The dynamic response of HYWIND Demo due to the combined action of wind and waves is numerically simulated by the computational tool SIMA (Simulation of Marine Operations). The numerical model has previously been compared to full scale measurements by Skaare et al. [1]. To better understand the sensitivity of the responses to the various environmental parameters, a sensitivity study is performed. In this preliminary study, the sensitivity of various motion parameters are investigated as function of the wave conditions, wind speed, turbulence intensity, wind shear as well as the spatial resolution of the numerical wind field. A more comprehensive study is under way.

Objective

This study was conducted by performing sensitivity studies to identify the relative importance of each environmental parameter to the total structural responses of HYWIND Demo based on study made by Skaare et al. [1].

Methods

• The environmental conditions studied by Skaare et al. [1] are used as base cases. Both below rated and above rated wind speeds are considered. Firstly, results were checked to be consistent with the results in Skaare et al. Then, the environmental characteristics are varied around the values corresponding to the base cases while the length of simulations were 30min.

• Environmental parameters such as wave peak period and significant wave height, the exponent (α) in wind shear profile power law, the spatial resolution of the numerical wind field and turbulence intensity of wind were changed. To perform sensitivity study of a parameter, only that parameter was changed while other environmental parameters remained unchanged.

• For each parameter, responses of the structure such as electrical generator output, platform pitch motion at nacelle level and blade out-of-plane tip motion were recorded.

• Mean and standard deviation of each response were compared to understand the importance of each parameter.

Results

• Higher $H_s$ and $T_p$ generated higher standard deviation in evaluated responses. For instance, while mean platform pitch at nacelle level is almost the same equal to 1.55 degrees in all cases, Figure 1. shows that standard deviation of platform pitch at nacelle level in case 9 where $H_s=0.75m$ and $T_p=6.5s$ is 1.49 degrees compared to 0.22 degree for case 1 where $H_s=12.25$ and $T_p=15.5s$.

• Higher turbulence intensity produced higher standard deviation in evaluated responses. For example, it is shown in Figure 2. that by increasing the turbulence intensity from 5% to 15%, the standard deviation of electrical generation output increases from 0.1275 to 0.341 MW, while the mean electrical generation output slightly decreases from 1.339 to 1.291 MW.

• Varying $\alpha$ in wind shear profile power law and the spatial resolution of the numerical wind field had no significant effect on the responses.

Conclusions

• The wave characteristics and turbulence intensity had significant influence on the dynamic behaviour of HYWIND Demo. However, within the range of parameters considered in this study, the wind shear exponent, alpha, and the spatial resolution of the numerical wind field did not show to have any significant impact on the dynamics. However, more detailed analysis is planned to investigate the impact of the wind field parameters on the dynamic response.

• High turbulence intensity of wind could be an important player that variation of alpha has no significant effect on the responses. For instance, when turbulence intensity reduced from 11 % to 1% in above the rated wind speed base case, Figure 3. shows that the standard deviation of blade out-of-plane tip motion increased from 15.98 to 22.85 cm when $\alpha$ increases from 0 to 0.14.

References

Parameter Estimation of a Breaking Wave Slamming Load Model using Monte Carlo Simulation

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2 University of Stavanger, Kjell Arholmsgate 41, 4036 Stavanger, Norway

Introduction

- Offshore wind turbines (OWTs) are installed in intermediate and shallow water with occurrence of breaking waves.
- OWTs subjected to the breaking wave, especially plunging breakers, are excited by an impulsive impact force referred to as the slamming load influencing the design loads significantly.
- Engineering model of the slamming load with significant parameter variabilities [1, 2]:
  \[
  F(t) = \lambda \cdot \eta_0 \cdot C_s \cdot C_r \cdot T \cdot \left(1 - \frac{t}{T}ight)
  \]

Objective: Estimate the governing parameters: Slamming Coefficient \( C_s \), Curling Factor \( \lambda \) and Impad Duration \( T \) by a combination of large-scale experimental data and numerical simulations performed with the MonteCarlo method.

Methodology: Estimate the parameters from 5000 random MC combinations of the three parameters by comparing simulated response in HAWC2 against the measured response from a large-scale experiment.

- Monte Carlo Simulations: 5000 simulations with an independent, uniform distributed input parameters of \( C_s \) (0.5π – 2.5π), \( \lambda \) (0.3 – 0.5) and \( T \) (0.02 – 0.26).

Large-Scale Experiment

- Experiment setting: regular wave (H 1.5m, T 4s, D 1.5m), sloped wave tank.
- Experiment data: wave elevation at pile, measured force at pile top and bottom. Repeated wave packets include nonbreaking wave and breaking wave.

Numerical Simulation

- OceanWave3D: fully nonlinear potential flow solver at DTU Mechanical. The wave surface elevation and wave particle kinematics are obtained.

- HAWC2: Aero-Elastic-Hydro Code at DTU Wind Energy. The quasi-static force is calculated using Morison equation associated with wave kinematics from OceanWave3D. The responses simulated from 5000 Monte Carlo simulations are quantified against experimental responses using RMSE.

Results

- Wave surface elevations simulated in OceanWave3D agree well with experimental data. Response force for a non-breaking wave are simulated in HAWC2 with the wave kinematics from OceanWave3D showing good agreement with measurements.

Conclusions

- OceanWave3D reproduces highly nonlinear wave elevation with good agreement.
- The Morison’s equation is able to calculate steep non-breaking wave force with wave kinematics from OceanWave3D.
- The slamming coefficient \( C_s \) and curling factor \( \lambda \) are close to values in Winck-Oumeraci model.
- Slamming load impact duration \( T \) is significantly larger than the values found by the Goda and Winck-Oumeraci model, which decides the dynamic amplification for OWTs.
- For OWTs located in areas where breaking waves are present, a flexible structure is recommended to eliminate its dynamic amplifications.

References


Acknowledgement

This study is a part of the project DeRisk (Grant Number 4106-00038B), which is funded by Innovation Fund Denmark. Further funding is provided by Statoil and the participating partners. All funding is gratefully acknowledged.

Table 1. Statistics of the estimated parameters (case 1-8)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Slamming Coefficient ( C_s )</th>
<th>Impact Duration ( T )</th>
<th>Curling Factor ( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.89π</td>
<td>1.95 R/C</td>
<td>0.39</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.21π</td>
<td>0.35 R/C</td>
<td>0.02</td>
</tr>
<tr>
<td>Goda</td>
<td>( \pi )</td>
<td>R/C</td>
<td>0.40</td>
</tr>
<tr>
<td>Winck-Oumeraci</td>
<td>( 2\pi )</td>
<td>13 R/32C</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Fig 1. Breaking wave induced slamming load

Fig 2. Experimental set up in GWK [3]

Fig 4. Measured wave elevation and total response force (left). Decomposition of slamming load response from total force measurement for a breaking wave (right)

Fig 6. Wave surface elevations simulated in OceanWave3D agree well with experimental data. Response force for a non-breaking wave are simulated in HAWC2 with the wave kinematics from OceanWave3D showing good agreement with measurements

Fig 7. Estimated parameters for all breaking wave packets in the experiment

Fig 3. Numerical set up in OceanWave3D

Fig 5. Verified pile model set up in HAWC2 with first NF around 19Hz

Fig 8. DAF is dependent on time ratio
Model scale testing of offshore wind turbines is challenging due to the incompatibility between Froude and Reynolds scaling. Real-Time Hybrid Model (ReaTHM®) testing is an experimental method where numerical simulations are combined in real-time with model testing. Using this method alleviates the scaling issue since the aerodynamic loads are simulated and applied on the physical model by use of six winches and lines connected to the tower top. These loads are calculated by FAST, and include the elasticity, aerodynamics and control system. Prior to the test in the Ocean Basin, the ReaTHM® tests are emulated by simulating the physical part of the experiments. This is an important step in the design of the experiments, used to verify the complete hybrid testing loop, to ensure the quality of the tests to be performed.

The emulated testing prior to the hybrid tests in the ocean basin is valuable both for increased quality of the tests and for the safety. It is possible to investigate the tension in the wires prior to the tests and establish that they are within the maximum and minimum levels. The tests giving the highest tension loads were the extreme wind tests; extreme operating gusts (EOG) and extreme coherent gust with direction change (ECD). The tension in the wind lines for the emulated ECD test is shown in Figure 4.

The effect of flexible blades compared to stiff blades was also investigated. In the left graph of Figure 5, the blade tip deflection of a stiff blade (no elasticity), a flexible blade (only the first flapwise mode of the blade included) and the full-flexible blade (first and second flapwise mode and the first edgewise mode are activated) are shown. The difference between the fully flexible blade and the flexible blade is small, however the difference is large for a stiff blade, around 8 m. This has an effect on the global response of the blade, as well as the platform, which is illustrated in the right graph of Figure 5. Here the spectra of the platform pitch is shown for one turbulent wind case, and one can see that the platform pitch response is dependent on the elasticity of the blade. The flexible blade was chosen for the hybrid tests as this provided an increase in accuracy, but kept the computational time to a low level. It is important to limit the computational efforts since the hybrid tests are real-time and downscaled.

Acknowledgement

Also, we are grateful to Dr. techn. Olav Olsen AS for the permission and contribution to set up the public 10MW semi-submersible design based on their concept of the OO-Star Wind Floater (www.olavolsen.no).

Referencer


Discussion

An overview of the emulated hybrid system is shown in Figure 1. Loop 1 is the emulated physical experiments performed in SIMA. Loop 3 computes the aerodynamical loads based on the measured platform motions and Loop 2 is allocating the aerodynamic loads to the six different winches (see Figure 2).

From Loop 1 the displacements and velocities of the tower top are sent to Loop 3. The displacements and velocities are calculated in SIMA[4]. A Simo model is made of the OO-Star Wind Floater in SIMA. Simo is a time domain simulation program for study of motions and station-keeping of multibody system developed at SINTEF Ocean [3].

The FAST module in Loop 3 estimates the rotor loads. The FAST module contains a dll of the FAST program (v8, with AeroDyn v14) developed at NREL, which is an aer-hydro-servo-elastic software [5]. Only the first flapwise mode is included in the aeroelastic calculation in FAST. The remaining elastic modes are stiff. The weight of the rotor is included in both the Simo model and in the FAST calculation, thus, the rotor loads transferred from the FAST module in Loop 3 does therefore not represent the gravitational and inertial loads.

The rotor loads are transferred from the FAST module in Loop 3 to the Allocation module in Loop 2. The Allocation module transfers the rotor loads to commanded line tension. The Force Controller module takes the line tensions as input and controls the winches to obtain the desired tension, which is sent to the SIMA module in Loop 1.

Hybrid testing of a semi-submersible floating wind turbine was conducted in the wave basin at SINTEF Ocean in fall 2017 as a part of the EU project Lifes50+[6]. The wind turbine tested was the OO-Star Wind Floater, which is developed by Dr. Tech Olav Olsen and is a semi-sub platform for floating wind turbines [1]. The platform consists of a star shaped pontoon, which connects the central column to three outer columns. The mooring system is a catenary system with three mooring lines. The rotor loads are transferred from the FAST module in Loop 3 to the Allocation module in Loop 2. The Allocation module transfers the rotor loads to commanded line tension. The Force Controller module takes the line tensions as input and controls the winches to obtain the desired tension, which is sent to the SIMA module in Loop 1.

Floating Offshore Wind Turbine Model

The OA-Star Wind Floater is a semi-submersible floating wind turbine with a 10 MW power rating. The platform consists of a star shaped pontoon, which connects the central column to three outer columns. The mooring system is a catenary system with three mooring lines. The rotor loads are transferred from the FAST module in Loop 3 to the Allocation module in Loop 2. The Allocation module transfers the rotor loads to commanded line tension. The Force Controller module takes the line tensions as input and controls the winches to obtain the desired tension, which is sent to the SIMA module in Loop 1.

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Figure 1: An overview of the emulated hybrid system.

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The FAST module in Loop 3 estimates the rotor loads. The FAST module contains a dll of the FAST program (v8, with AeroDyn v14) developed at NREL, which is an aer-hydro-servo-elastic software [5]. Only the first flapwise mode is included in the aeroelastic calculation in FAST. The remaining elastic modes are stiff. The weight of the rotor is included in both the Simo model and in the FAST calculation, thus, the rotor loads transferred from the FAST module in Loop 3 does therefore not represent the gravitational and inertial loads.

The rotor loads are transferred from the FAST module in Loop 3 to the Allocation module in Loop 2. The Allocation module transfers the rotor loads to commanded line tension. The Force Controller module takes the line tensions as input and controls the winches to obtain the desired tension, which is sent to the SIMA module in Loop 1.

The effect of flexible blades compared to stiff blades was also investigated. In the left graph of Figure 5, the blade tip deflection of a stiff blade (no elasticity), a flexible blade (only the first flapwise mode of the blade included) and the full-flexible blade (first and second flapwise mode and the first edgewise mode are activated) are shown. The difference between the fully flexible blade and the flexible blade is small, however the difference is large for a stiff blade, around 8 m. This has an effect on the global response of the blade, as well as the platform, which is illustrated in the right graph of Figure 5. Here the spectra of the platform pitch is shown for one turbulent wind case, and one can see that the platform pitch response is dependent on the elasticity of the blade. The flexible blade was chosen for the hybrid tests as this provided an increase in accuracy, but kept the computational time to a low level. It is important to limit the computational efforts since the hybrid tests are real-time and downscaled.
Multiple-degree-of-freedom actuation of rotor loads in model testing of floating wind turbines using cable-driven parallel robots

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ReaTHM® testing circumvents limitations of hydrodynamic laboratories, and in particular inherent issues of physical wind/wave testing of floating wind turbines. The rotor and wind field are numerical and interact in real time with the scale model subjected to physical hydrodynamic loads, by means of sensors and actuators.

Actuator requirements:
- Force-based (actuate loads, not motions)
- Multiple-degree-of-freedom (thrust, pitch and yaw moments, gen. torque, hor. shear force)
- Large workspace (follow the structure anywhere it moves)
- High accuracy and bandwidth (up to 3p frequency)

Cable-driven parallel robots (set of motor-winch-cable 1DOF actuators)

Lines should be kept in tension

One more line than actuated load components

1. From where and in which direction should they pull on the structure?
2. How to allocate tensions from rotor loads, and how to control pretension?

Line tension setpoint vector = f(motor locations, line attachment point locations on structure, motions, loads to actuate, pretension)

NOWITECH setup

LIFESS0+ setup

Design

Allocation strategy

Minimize Euclidean norm of line tension setpoint vector: stay close to reference

Similarity with physical rotor: Intuitive

Convenient

Specify tension on one particular line

Intuitive

Perfomant

Minimize higher-order norm of line tension setpoint vector: stay away from slack and peaks

Power spectral densities of Euclidean and infinite norms of commanded tension vector at near-cutout condition (25 m/s), from LIFESS0+ model tests

Results

1. Line tensions need to adjust for changes in model orientation more with the LIFESS0+ setup than with the NOWITECH one

Higher line tensions, as a drawback among the many advantages of the LIFESS0+ setup

• The intuitive strategy (setting line 4 to reference tension in NOWITECH setup) gives physical meaning to the cost of much higher tensions

• Using higher-order norm as minimization objective is significantly more effective in keeping tensions further away from slack and excessively high values than using the Euclidean norm. The tensions still stay close to reference when using higher-order norms. It should be used

• The choice of the norm to minimize is less important for the NOWITECH setup

References


Line nr Function
1 Thrust force/2 + Pitch moment/2d N + Pretension
2 Pitch moment/2d N – Yaw moment/2d N + Pretension
3 Thrust force/2 – Yaw moment/2d N + Pretension
4 Pretension
5 Generator torque/2dT + Shear force/2
6 Generator torque/2d T – Shear force/2

Coefficient line nr i Load component
\( (1/2)(x + y/2) \)
Thrust force
\( (1/2)(x + y/2) \)
Shear force
\( (1/2)(x + y/2) \)
Generator torque
\( (1/2)(x + y/2) \)
Pitch moment
\( (1/2)(x + y/2) \)
Yaw moment

KPN Hybrid

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A 6DoF hydrodynamic model for real time implementation in hybrid testing

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Abstract
This work deals with the numerical approach and technical implementation of the 6-DoF hydrodynamic model, which is combined with the Politecnico di Milano HexaFloat robot (Fig.1,2), adopted for wind tunnel Hybrid/HIL tests floating offshore wind turbines. The wind tunnel hybrid testing methodology, along with its ocean-basin counterpart [1], is currently being considered as a valuable upgrade in the mode scale experiments, for its capability to reduce the effect of the typical scaling issues of such systems. The work reports an overview of the setup and the testing methodology, presenting briefly the main challenges about the deployment on the real-time hardware and summarizing the key solving choices. A set of results related to code-to-code comparison between the optimized HIL numerical model and the reference FAST computations are included, confirming the correctness of the approach.

1 Numerical model
Equations of motions:

\begin{equation}
[M_{x} + A_{x}] \ddot{x} + [K_{x}] x + [E_{x}] \dot{x} = [F_{x}] \quad (1)
\end{equation}

(1) aerodynamic forces \(F_{x}\), measured by dynamometric balance \(F_{corr}\) placed at the tower’s base combined with a correction \(E_{x}\) due to inertial and gravitational contributions of the scale model (no Froude scaling):

\begin{equation}
[L_{x}] \dot{x} = [M_{x}] \quad (2)
\end{equation}

\begin{equation}
[L_{y}] \ddot{y} = [M_{y}] \quad (3)
\end{equation}

\begin{equation}
[L_{z}] \ddot{z} = [M_{z}] \quad (4)
\end{equation}

Platform radiation, diffraction and viscous forces \([L_{y}, L_{z}]\) and \([M_{y}, M_{z}]\) are implemented as in [4] (extended to 6-DoF). Mooring line forces \([M_{x}]\) are included through a lumped-mass model, as in [8], where the internal nodes’ contributions are: tensile load \(T_{\text{rad}}\) damping \(C_{\text{rad}}\) weight \(M_{\text{rad}}\) contact with seabed \(B\) and viscous drag forces \(D\) depending on the node’s position \(x\) and/or velocities \(\dot{x}\):

\begin{equation}
[M_{x}] = [E_{x}] + [L_{x}] + [F_{x}] \quad (5)
\end{equation}

\[M_{x}] = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & M_{15} & M_{16} \\ M_{21} & M_{22} & M_{23} & M_{24} & M_{25} & M_{26} \\ M_{31} & M_{32} & M_{33} & M_{34} & M_{35} & M_{36} \\ M_{41} & M_{42} & M_{43} & M_{44} & M_{45} & M_{46} \\ M_{51} & M_{52} & M_{53} & M_{54} & M_{55} & M_{56} \\ M_{61} & M_{62} & M_{63} & M_{64} & M_{65} & M_{66} \end{bmatrix} + \begin{bmatrix} E_{11} & E_{12} & E_{13} & E_{14} & E_{15} & E_{16} \\ E_{21} & E_{22} & E_{23} & E_{24} & E_{25} & E_{26} \\ E_{31} & E_{32} & E_{33} & E_{34} & E_{35} & E_{36} \\ E_{41} & E_{42} & E_{43} & E_{44} & E_{45} & E_{46} \\ E_{51} & E_{52} & E_{53} & E_{54} & E_{55} & E_{56} \\ E_{61} & E_{62} & E_{63} & E_{64} & E_{65} & E_{66} \end{bmatrix} + \begin{bmatrix} F_{11} & F_{12} & F_{13} & F_{14} & F_{15} & F_{16} \\ F_{21} & F_{22} & F_{23} & F_{24} & F_{25} & F_{26} \\ F_{31} & F_{32} & F_{33} & F_{34} & F_{35} & F_{36} \\ F_{41} & F_{42} & F_{43} & F_{44} & F_{45} & F_{46} \\ F_{51} & F_{52} & F_{53} & F_{54} & F_{55} & F_{56} \\ F_{61} & F_{62} & F_{63} & F_{64} & F_{65} & F_{66} \end{bmatrix}
\end{equation}

The mass matrix \([M]\) includes also the hydrodynamic added masses of each node \(n\):

\begin{equation}
[M_{x}] = \begin{bmatrix} m_{1} + [a_{1}] \quad m_{2} + [a_{2}] \quad m_{3} + [a_{3}] \quad m_{4} + [a_{4}] \quad m_{5} + [a_{5}] \quad m_{6} + [a_{6}] \end{bmatrix}
\end{equation}

2 Modelling optimization
Simplification of the model, without loosing physical consistency, is required due to real-time constraints. As an example, the importance of each contribution of Eq.5 is evaluated for combined decay tests.
Kalman estimation of position and velocity for ReaTHM testing applications

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Introduction

• Model testing can reduce the costs of offshore wind turbines (OWTs).
• Real-time hybrid model (ReaTHM) testing provides solution to challenges related to such tests.
• The system is divided into physical and numerical substructure.
• State estimator is designed to estimate and filter the positions and velocities of the physical substructure.

Numerical Model

Two different versions of the system are designed for tests using virtual and physical data:

- Kinematic model
  - Can represent the motion of any floating structure in 6-DOF.
  - Plant model intended to simulate the physical system is implemented using the same state-space matrices.
  - State vector consists of the variables to be estimated.
  - Output vector consists of the variables which can be measured.
  - System matrices are defined according to Fossen [1].
  - Simplified model for tests with SIMA: linear and time-invariant.

Estimator design

- Kalman estimator chosen since it provides optimal estimates, minimizing the estimation error in the statistical sense.
- Both steady-state and time-varying versions are designed, implemented in MATLAB and tested.

Sensitivity analyses using virtual data

Sensitivity analyses addressing the robustness towards different types of disturbances are performed to identify the limits of the estimator. Time-varying Kalman estimator used for signal loss, otherwise steady-state version is used.

Validation of estimator using physical data

Both versions of the Kalman estimator are further tested against the laboratory experiments by Vilsen et al. [2]. Knowledge about delays and inaccuracies in the sensors used is taken into account.

Conclusions

- The generic kinematic model developed can recreate the SIMA simulated motions with reasonable accuracy.
- A Kalman estimator providing smooth and accurate position and velocity estimates in 6-DOF is designed, implemented and tested.
- The estimator is proven to be robust towards different types of disturbances.
- The estimator is able to estimate the states with a good accuracy, when compared with physical measurements.
- An improvement from the previously implemented estimators is demonstrated.

References

[1] Fossen T I 2011 Handbook of Marine Craft Hydrodynamics and Motion Control (Chichester, UK: John Wiley & Sons, Ltd.)
Numerical modelling and validation of a semisubmersible floating offshore wind turbine under wind and wave misalignment

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1. Introduction

Coupled aero-hydro-servo-elastic simulation tools play important role in the design of offshore floating wind turbines. For rational design of the system, accuracy of the numerical tool is important in predicting the system responses. While the load cases where the wave and wind are aligned are sometimes the largest contributor to the design, evaluation of the load cases where the wind and wave are in misaligned condition are also required in the design codes. In this study, first a series of water tank test is performed for a 1/50 scale semisubmersible floater and results for irregular wave tests with aligned and misaligned wind were analyzed. Then, an in-house numerical tool, NK-UTWind is used to model the full scale system, and results for aligned and misaligned cases are validated.

2. Water tank test

The water tank test were conducted using a 1/50 scale semisubmersible floater with 2MW wind turbine at Ocean Engineering Basin of National Maritime Research Institute, Japan, in July 2011. To simplify the effect from the moorings, tout mooring was chosen for the system.

3. Numerical modelling

NK-UTWind is an in-house code of coupled analysis for floating offshore wind turbine developed by ClassNK and University of Tokyo. The code solves the equation of motion for wind turbine support structure modelled with FEM beams. The hydrodynamics for the platform is evaluated with Morison equation, and the forces from the wind turbine calculated with FAST are passed to NK-UTWind as tower top loads. The mooring lines are modelled using linear spring in this study. The added mass coefficient Cm and the drag coefficient Cd in Morison equation as well as the Rayleigh damping term were calibrated using the free decay tests. Most of the calibrated coefficients were in the range of theoretical values for cylinders. Rayleigh damping was obtained as 2.5% from the results of linear damping coefficients.

4. Results

Comparison of the calculated and measured floater motions for aligned and misaligned wind and wave conditions are shown in the figures below. Measured motions in surge, heave, and pitch are similar for the aligned and misaligned cases, while sway and roll motion were dominated by components in the natural frequency for the aligned case, while the wave frequencies are also excited for the misaligned case. Calculations agreed well with the measurement for the roll motion, while several peaks were not captured by the calculation for the sway motion.

5. Conclusion

Measured surge, heave, and pitch motions and tower-base Fx and My loads are similar for the aligned and misaligned cases, and were well reproduced by the calculation. Measured sway and roll motion and tower-base Fy and Mx loads were dominated by components in natural frequency for the aligned case, while the components in wave frequencies increase for the misaligned case. Calculation agreed with the measurement for roll motion, while other responses needed further investigation.
Impact on wind turbine loads from different down regulation control strategies

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Abstract

Three characteristic derating strategies on the upstream wind turbine are studied and the load impact to the downstream one is assessed. These are defined as minimum/maximum rotor speeds (minRS, maxRS) and minimum thrust (minT) modes. Derating factors of 20% and 40% on available power are applied together with 4 and 7 diameters WT interspace. The study is based on aeroelastic simulations of a 2MW generic WT model including wake effects. The results show that below rated wind speed (8m/s) the downstream WT blade flap fatigue loads are minimized when the upfront WT is derated with the minRS strategy. The maxRS mode returns always the highest loads. When the WTS are aligned with the wind direction (full wake situation) the load levels for minRS and minT strategies are almost equal. Above rated wind speed (16m/s) the tendency is the same as at 8m/s. Finally, the fore-aft fatigue loads on the tower base and the main bearing yaw moment follow the same trends as the blade for both below and above rated wind speed.

Objective

Power down regulation can be done in different ways by adjusting the rotor speed and blade pitch angle on the individual turbines, which affect the fatigue loads on the turbine components. Until now the main focus was on power optimization [4, 5] and there has been limited documentation on the load variations as a result of different down-regulation strategies on wind turbines under wakes.

Main objective: Load impact for three characteristic derating strategies on the upstream WT to the downstream one

Method

- High fidelity aeroelastic simulations
  - HAWC2 - including the Dynamic Wake Meander model (DWM) [1, 2, 3]
  - Generic 2MW Wind Turbine (WT)
  - Two WTs in wind farm configuration
  - Upfront WT-2 is down-regulated, downstream WT-1 normal operation
- Wind farm derating control strategies
  - minimum/maximum rotor speeds (minRS, maxRS)
  - Minimum thrust (minT)
- Cases
  - Down regulation by 20% and 40% on available power
  - WT interspaces of 4 and 7 Diameters (D)
  - Ambient wind speed and direction: 8m/s, 16m/s and ±15 degrees

Results

- Equivalent fatigue loads on downstream WT-1
  - Blade root flapwise BM
  - Tower base fore-aft BM
  - Main bearing yaw moment

- Below rated wind speed (8m/s) the downstream WT blade flap loads are minimized when the upfront WT is derated with the minRS strategy
- The maxRS mode returns always the highest loads variations
- The load levels for minRS and minT strategies are almost equal when the WTS are aligned with the wind direction (full wake situation)
- Above rated wind speed (16m/s) the tendency is the same as at 8m/s
- Tower base fore-aft fatigue loads and main bearing yaw moment follow the same trend as the blade for both below and above rated wind speed.

Conclusions

References


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