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.
Tools for tomorrow's FOWT industry

Accuracy

Physical world

Numerical world

Design

High-fidelity models

State-of-the-art models

Simplified models

Cascading

Lab-scale tests

Full-scale measurements

Resources
Two public floaters – in FAST

- At L50+ web site (report D4.5)
- At DTUs GitLab site (models):
- Nautilus has released public FAST model too
Two public models – work done

- Tower modal analysis
- Hydrodynamic analysis
- Mooring model
- Controller adaption
Example: Nautilus step wind test

- LIFES50+ D4.5
The QuLAF pre-design model (2000 x real time speed)

**FAST (aeroDyn, tower, blades)**
- Precompute 3DOF rotor loads
- Determine aerodynamic damping: decay tests in turbulent wind
- Compute tower mode shape

**WAMIT**
- Compute standard A, B, C, X as fnc of frequency

**FAST (MoorDyn)**
- Linearize mooring forces around equilibrium point

FFT-based linear solver – 4 DOFs
- Solve in frequency domain and IFFT back to time domain

• PEGALAJAR-JURADO, BORG & BREDMOSE (2018)
Performance study

Max nacelle acceleration wave dominated. Under-predicted up to 25%, due to too large aero-damping.

Largest tower-base bending moment at rated wind speed. Matched very well by QuLAF.

Surge matched well.

- Madsen, Pegalajar-Jurado & Bredmose (2019)
Numerical optimization

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Resources
Low-Order Modeling: Applications

- Rigid body + potential flow
- Low-order coupled FOWT model
- Coupled state-of-the art model

\[ F = m\ddot{\vec{V}} + c\dot{\vec{V}} \]
Simplified Low-Order Wind Turbine Model (SLOW)

- **Structural model**: elastic Multibody System, 5 DOFs (2D y-z-plane)
- **Aerodynamics**: rigid, quasi-static, rotor-effective wind, rotationally sampled turbulence
- **Hydrodynamics**: panel code coefficients, simplified radiation model, Morison equation, parametric drag
- **Mooring lines**: nonlinear, quasi-static
- **Control**: generator torque + blade pitch
- **Formulation**: nonlinear + linear

LEMMER (2018)
Simplified Low-Order Wind Turbine Model (SLOW)

- Extreme operating gust, still water, DTU10MW + TripleSpar, good agreement of transient response with FAST

LEMNER (2018)
Simplified Low-Order Wind Turbine Model (SLOW)

- Irregular waves, NAUTILUS-DTU10, good agreement between SLOW, FAST and experiment at SINTEF Ocean of LIFES50+
Simplified Low-Order Wind Turbine Model (SLOW)

- Irregular waves, turbulent wind above rated, DTU10MW + TripleSpar, good agreement between SLOW and FAST in stochastic conditions

LEMMER (2018)
Integrated Optimization

- Parameterization of:
  - Steel design
  - Hydrostatics
  - Panel code
  - Controller
Integrated Optimization: Viscous Effects

• Parametric hydrodynamic viscous drag

• Iterative controller tuning based on updated viscous drag coefficients
Automated controller design:
- Determine stability limit at each operating point
- Obtain robust gain scheduling, tailored to FOWT
Automated controller design:
- Determine stability limit at each operating point
- Obtain robust gain scheduling, tailored to FOWT
Wave forces: Favorate harmonic response behavior through hull shape design
Drift forces: Controller can damp slow-drift response

LEMMER (2017)
Integrated Optimization

- Instantaneous center of rotation at hub through hull optimization
- No fore-aft motion from wave forcing

LEMME (2019)
Extreme waves – Hs=10.9m Tp=15s

Waves-only

State-of-the-art FAST model

2nd-order wave forcing
• Newman Approximation
• Full Quadratic Transfer Function (QTF)

LIFES50+ D4.8
Extreme waves – Hs=10.9m Tp=15s

Low frequency response at natural frequencies

Damping is important at natural frequencies

Approach:
• Decompose into modal response
• Calibrate modal damping to get right standard deviation

LIFES50+ D4.8; PEGALAJAR-JURADO & BREDMOSE (2019)
Extreme waves – $H_s = 10.9m$ $T_p = 15s$

95 % quantile
- 3% surge error
- 16% pitch error

You can get quite OK response by calibration.

Is Newman approximation as good as full Quadratic Transfer Function (QTF)?
Accuracy of Newman approximation

Newman approximation under-predicts

- Notably for surge and heave
- Strongly for pitch

Calibration can help. But a test is then required.
Advanced models

Accuracy

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Resources
Advanced modelling: Free wake aerodynamics

Experimental studies in windtunnel by Polimi

Simulation using a lifting line/free vortex approach
Investigation of unsteady aerodynamics
Simulation approach: Lifting Line/Free Vortex method (Tool: WInDS)
→ Capturing unsteady aerodynamics inherently
Comparison of experimental data (gathered by Polimi) with simulation results
Modelling of floater flexibility

- Material savings: Floater not fully rigid
- May alter global natural frequencies
- Especially tower frequencies

**Theoretical background**

- Large-volume body – linear potential flow & Cummins equation

\[
\left( \tilde{M} + \tilde{A}_\infty \right) \ddot{q}(t) + \int_0^t \tilde{L}(t - \tau) \dot{q}(\tau) d\tau + \tilde{K}_h q(t) = \tilde{f}_D(t) + \tilde{f}_{con}(t)
\]

- Rigid: 6 DOF body motion is considered
- Easily extended to include \(N\) flexible modes such that \(q\) contains \((6+N)\) states

\[
\Phi(x, y, z, t) = \Phi_i + \Phi_d + \Phi_r
\]

\[
\frac{\partial \phi_j}{\partial n} = i \omega n_j
\]

\[
\frac{\partial (\phi_d + \phi_i)}{\partial n} = 0
\]

Methodology

\[
\begin{align*}
\begin{bmatrix} \mathbf{M} + \mathbf{A}_\infty \end{bmatrix} \ddot{\mathbf{q}}(t) + \mathbf{C} \dot{\mathbf{q}}(t) + \int_0^t \mathbf{L}(t-\tau) \dot{\mathbf{q}}(\tau) d\tau + \left( \mathbf{K} + \mathbf{K}_b \right) \mathbf{q}(t) &= \mathbf{i}_D(t) + \mathbf{i}_{\text{con}}(t) \\
\end{align*}
\]

HAWC2

HAWC2

WAMIT

Engineer

HAWC2

Example: OO floater in DTUs HAWC2 model

Mixed mode - top blade is in phase with tower, one blade is in anti-phase and one does not move much.

Mode dominated by collective blade motion and smaller tower motion in phase with the blades. One downward blade moves much more than the others.

Fore-aft tower motion with collective blade-motion in anti-phase.
Wrap up
Research needs

• Improved methods for damping. Decay tests not sufficient.
• Simplified models has great potential
• Improved aerodynamic tools for FOWT
• Rational hydrodynamic CFD
• Exploit multi-fidelity approach in stochastic modelling
• Rational methods for test reproduction
Publications on simplified models

- Deliverable 4.1 Simple numerical models for upscaled design
- Deliverable 4.3 Optimization framework and methodology for optimized floater design


Publications on state-of-the-art models

• Deliverable 4.4 *Overview of the numerical models used in the consortium and their qualification*
• Deliverable 4.2 *Public definition of the two LIFES50+ 10 MW floater concepts*
• Deliverable 4.5 *State-of-the-art models for the two LIFES50+ 10MW floater concepts*
• Deliverable 4.6 *Model validation against experiments and map of model accuracy across load cases*


• Public models available at DTUs GitLab site
Publications on advanced models

• Deliverable 4.7 Models for advanced load effects and loads at component level
• Deliverable 4.8 Validation of advanced models and methods for cascading into simpler models
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