LIFES50+ Final Event Bilbao, 03 April 2019

Session: Experiments and numerical design
Topic: Numerical optimization

Henrik Bredmose – DTU
Frank Lemmer – University of Stuttgart

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.

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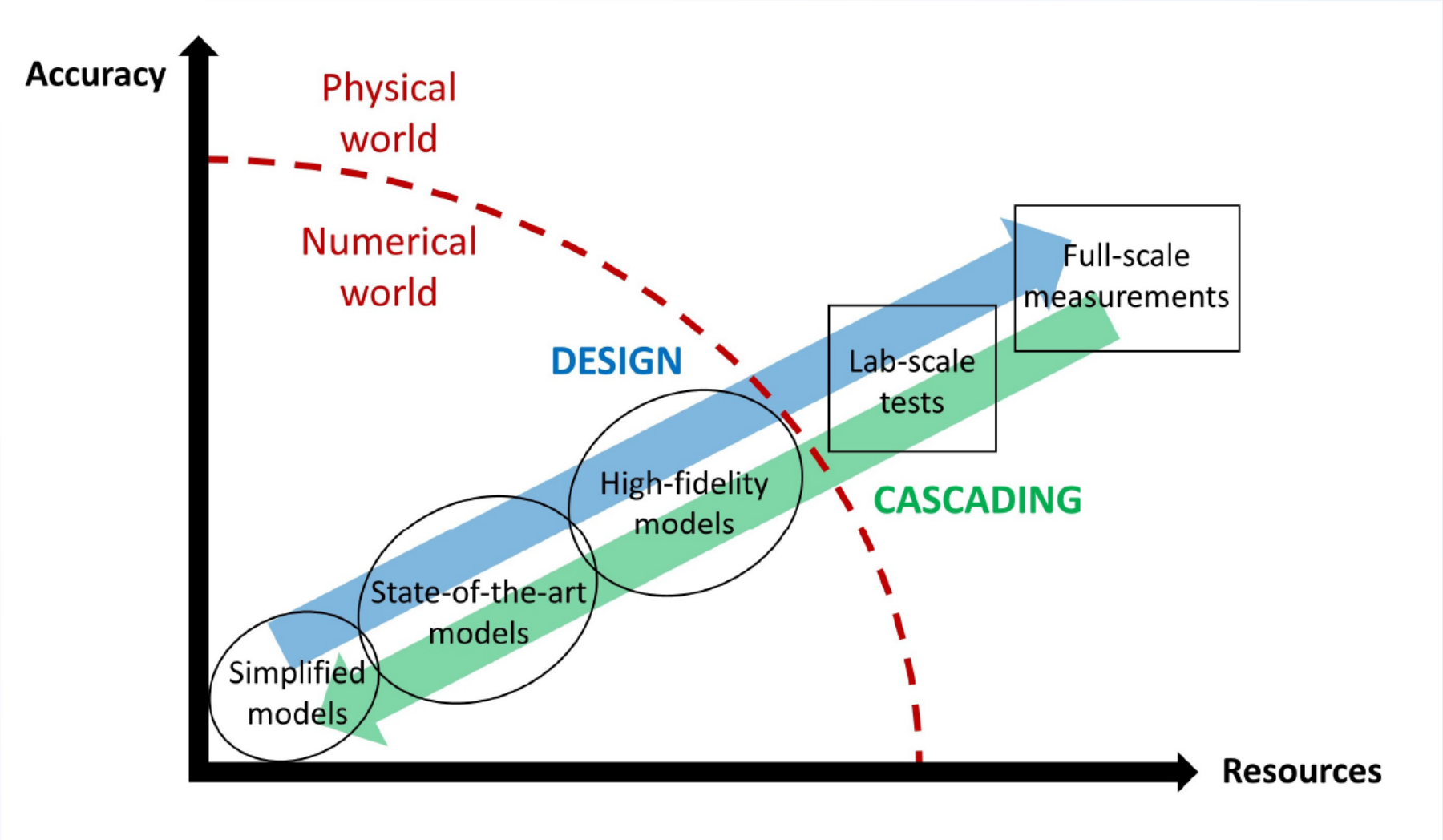
Tools for tomorrows FOWT industry



Two public floaters – in FAST

- At L50+ web site (report D4.5)
- At DTUs GitLab site (models):

  https://rwt.windenergy.dtu.dk/dtu10mw/dtu-10mw-rwt/tree/master/aeroelastic_models/fast.
- Nautilus has released public FAST model too

- LIFES50+ D4.5

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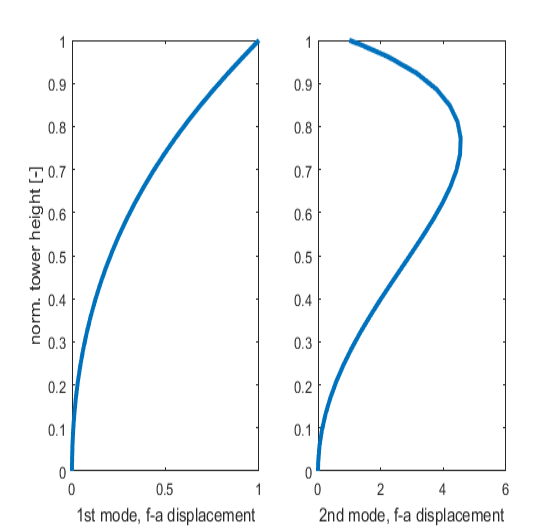
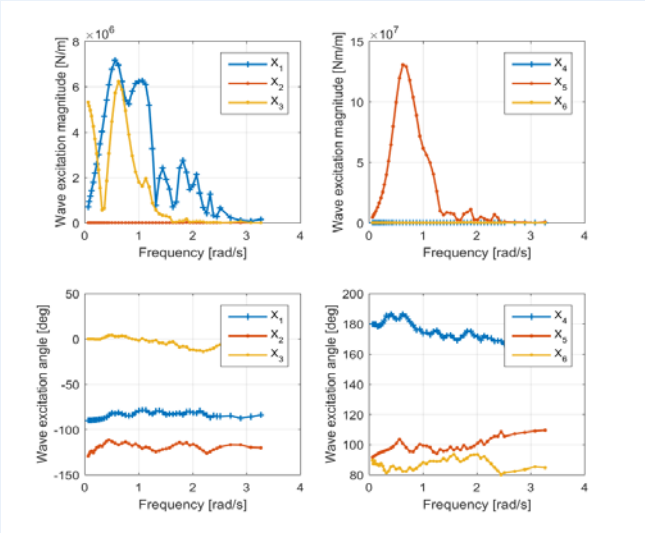
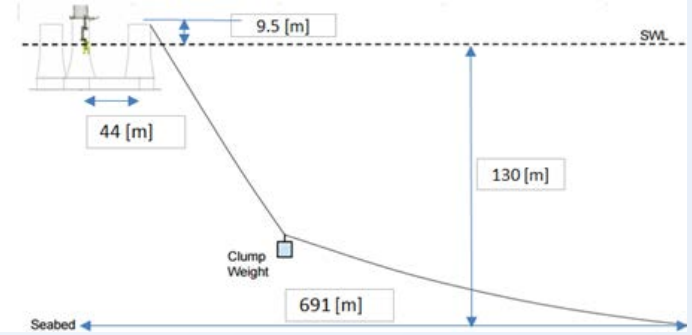
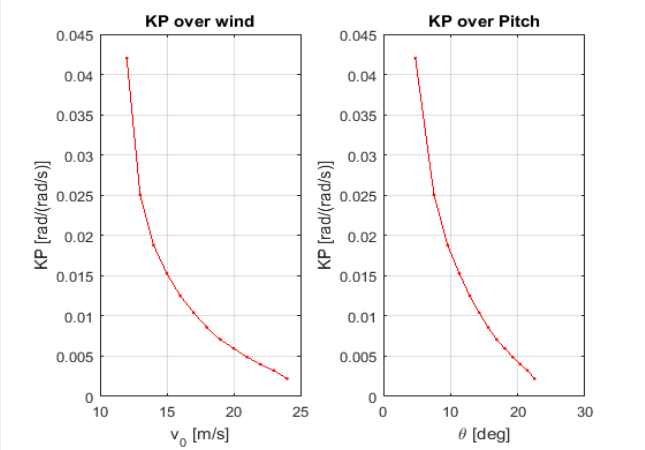
Two public models – work done

- Tower modal analysis
- Hydrodynamic analysis
- Mooring model
- Controller adaption









- LIFES50+ D4.5

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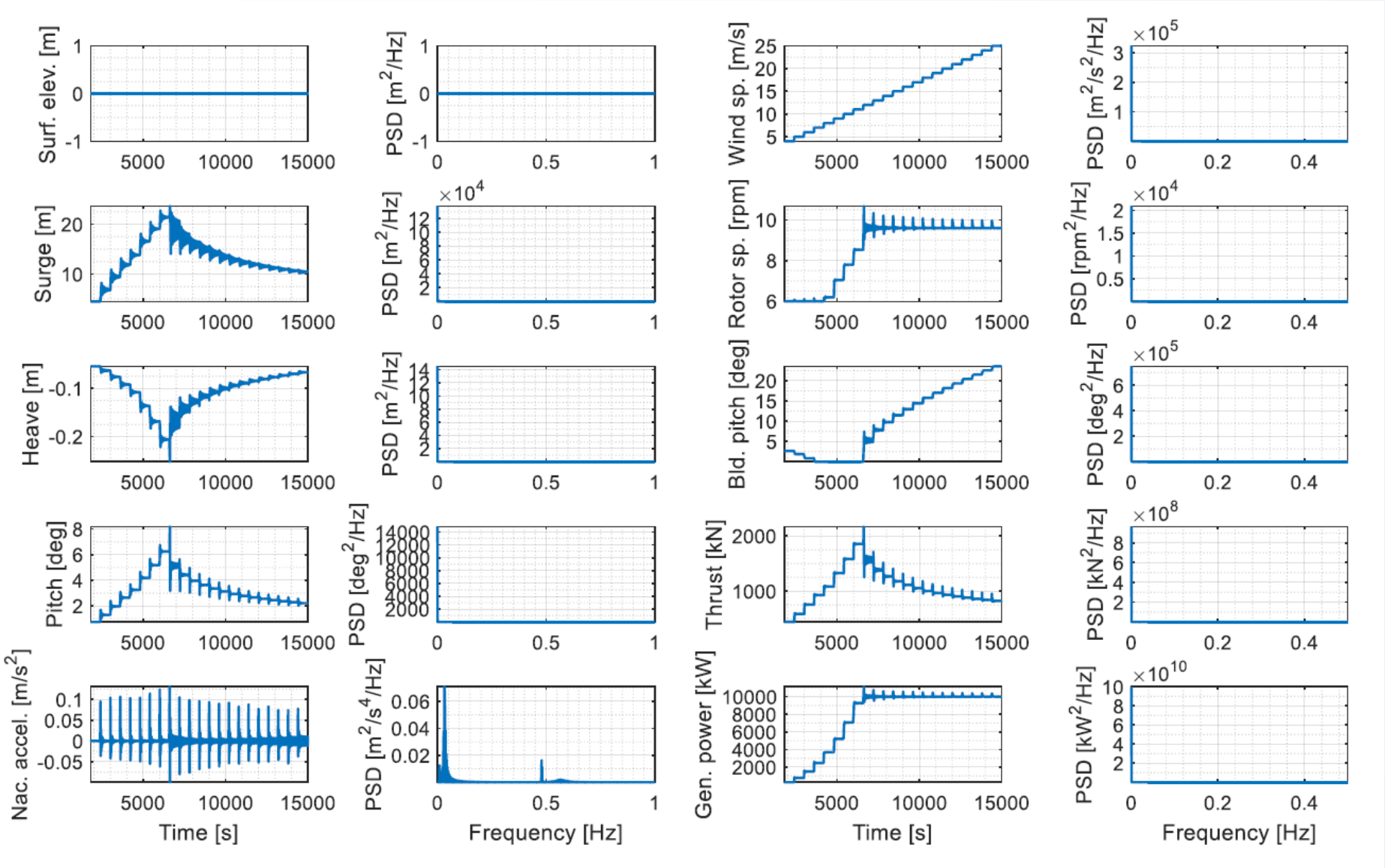
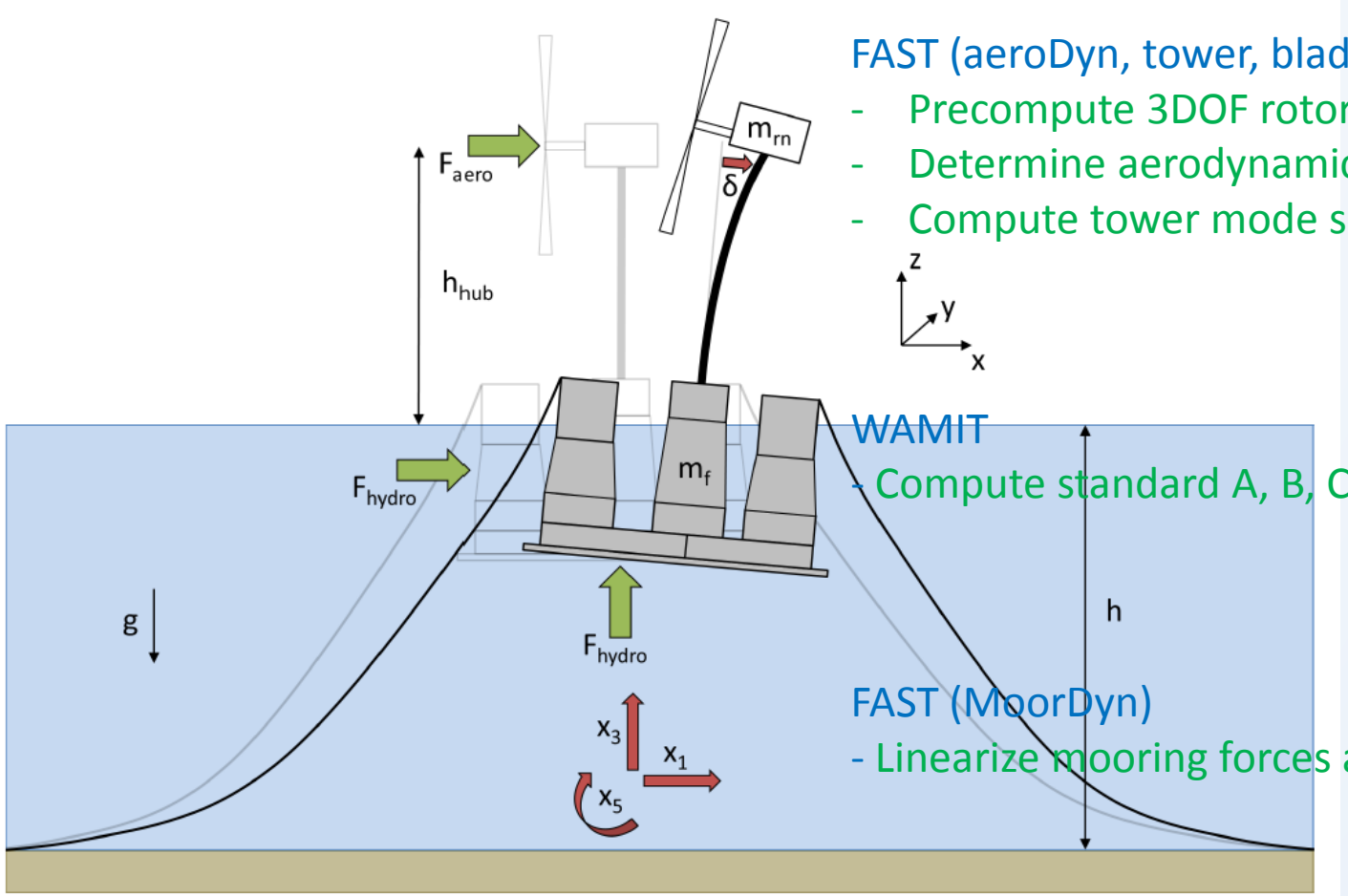
Example: Nautilus step wind test



- 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

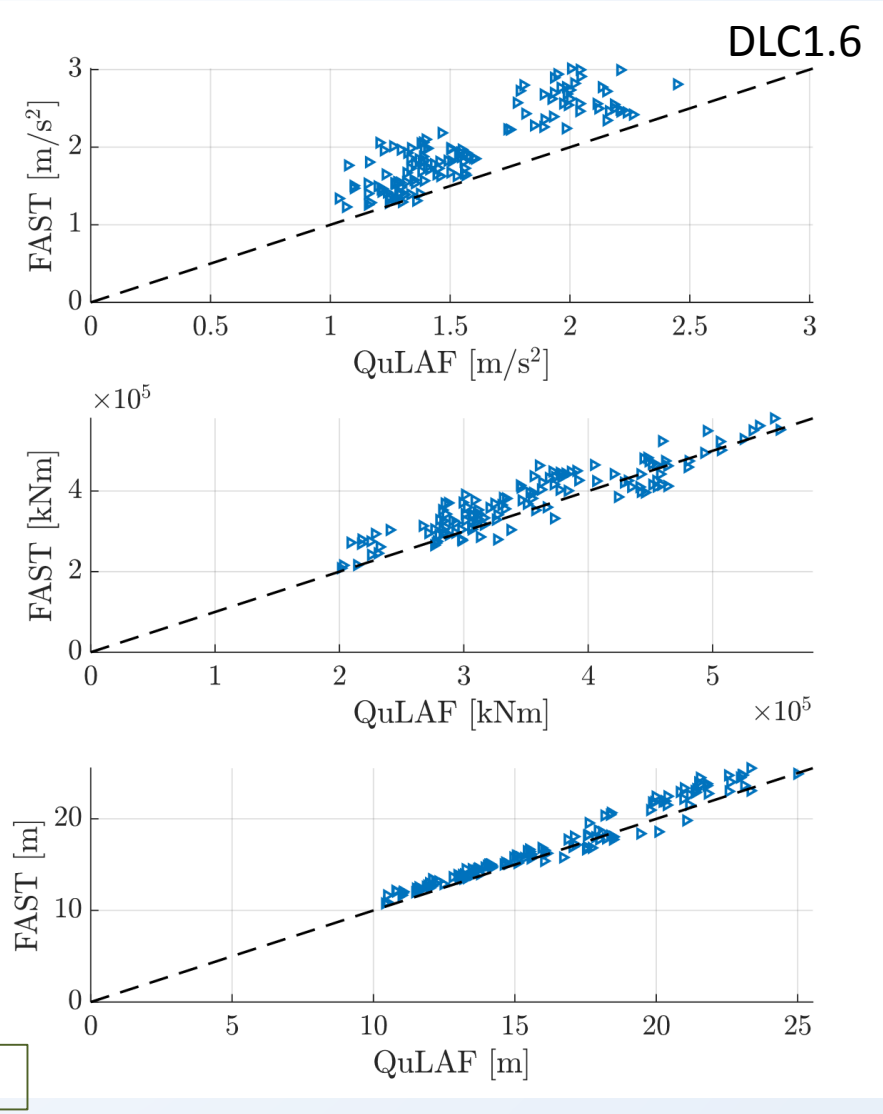
- Pegalajar-Jurado, Borg & Bredmose (2018)

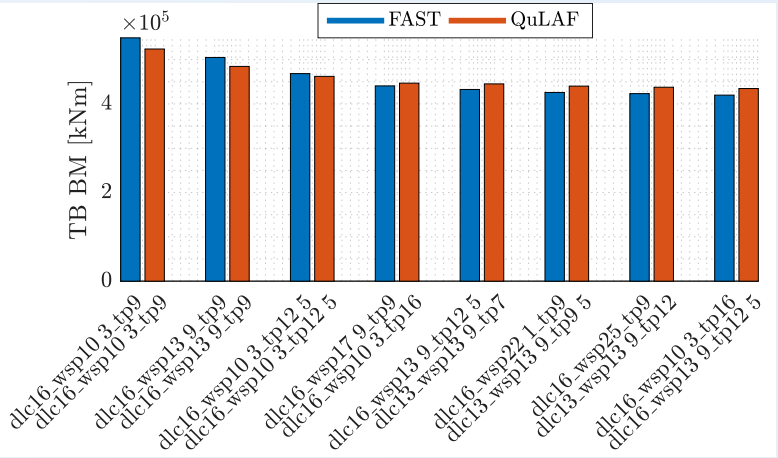
Performance study

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.

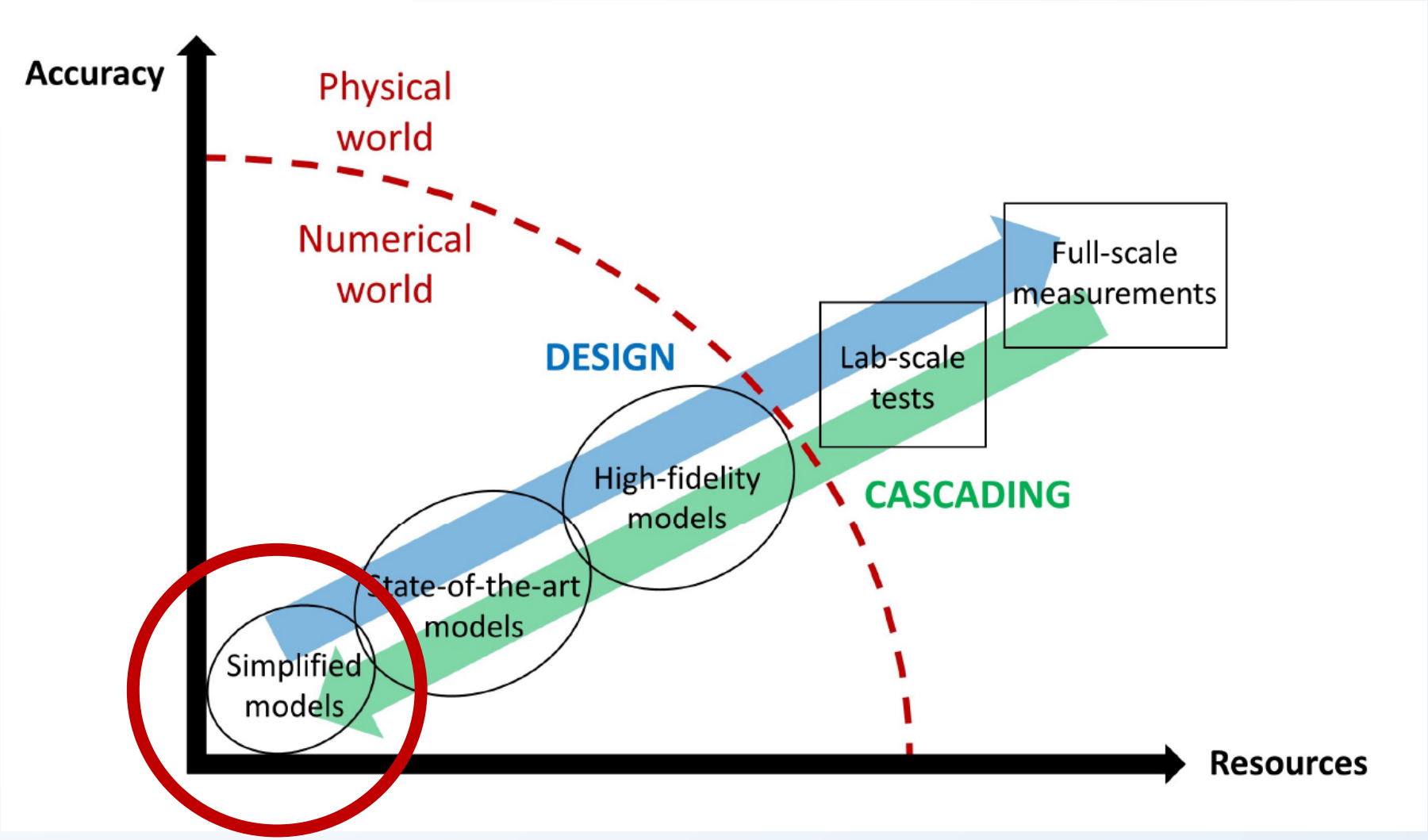
Surge matched well.





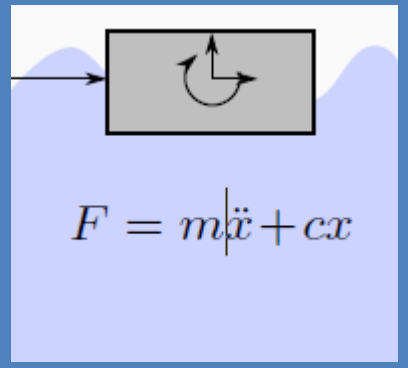
- MADSEN, PEGALAJAR-JURADO & BREDMOSE (2019)

Numerical optimization

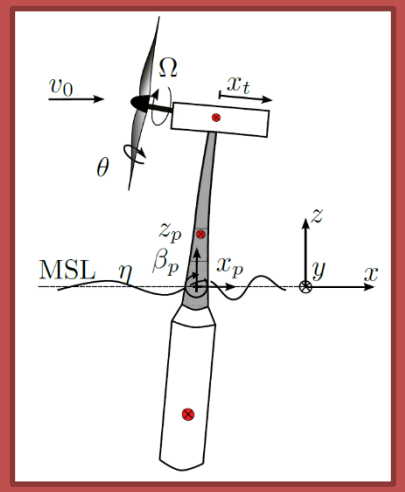


Low-Order Modeling: Applications

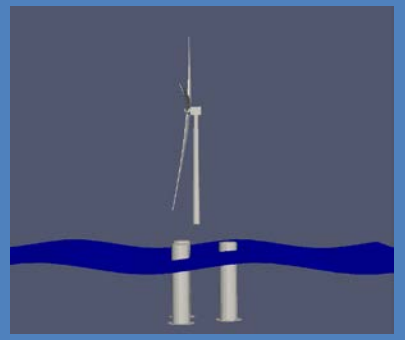
- Rigid body + potential flow



- Low-order coupled FOWT model

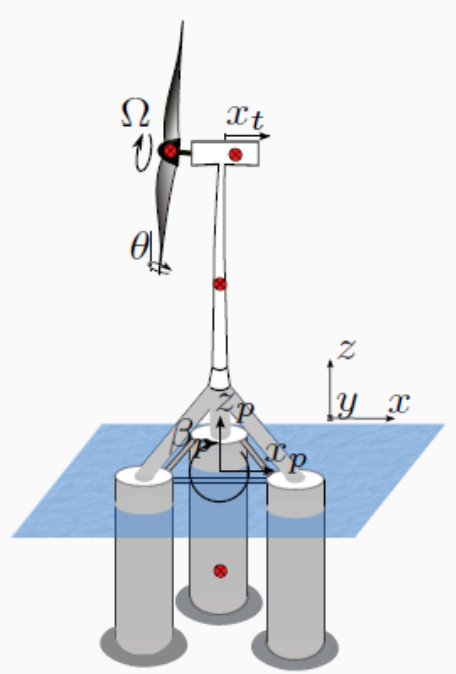


- Coupled state-of-the art model



Simplified Low-Order Wind Turbine Model (SLOW)

- Structural model: eastic 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



$$\boldsymbol{q} = [x_p, z_p, \beta_p, x_t, \Omega, \theta]^T$$

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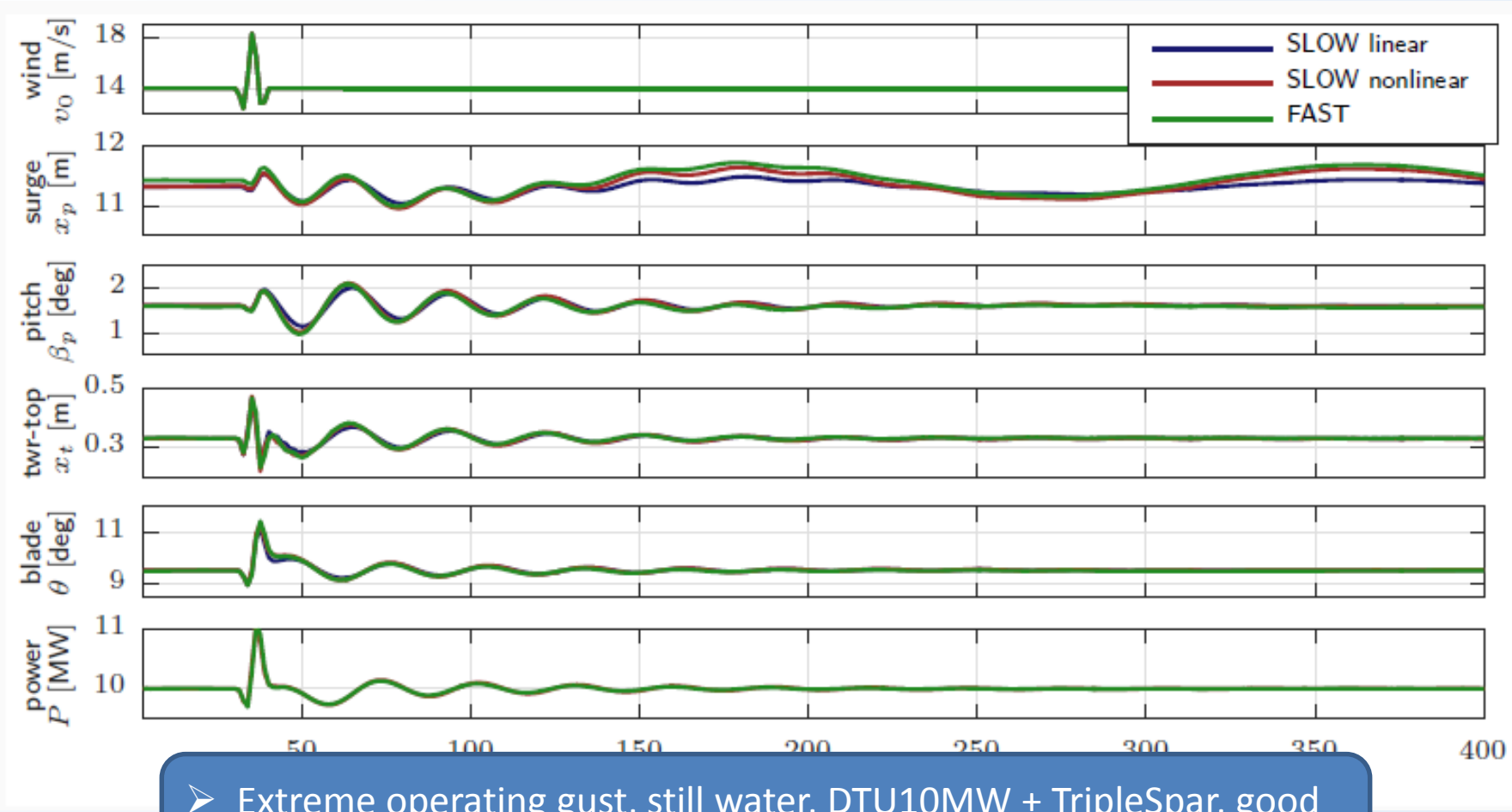
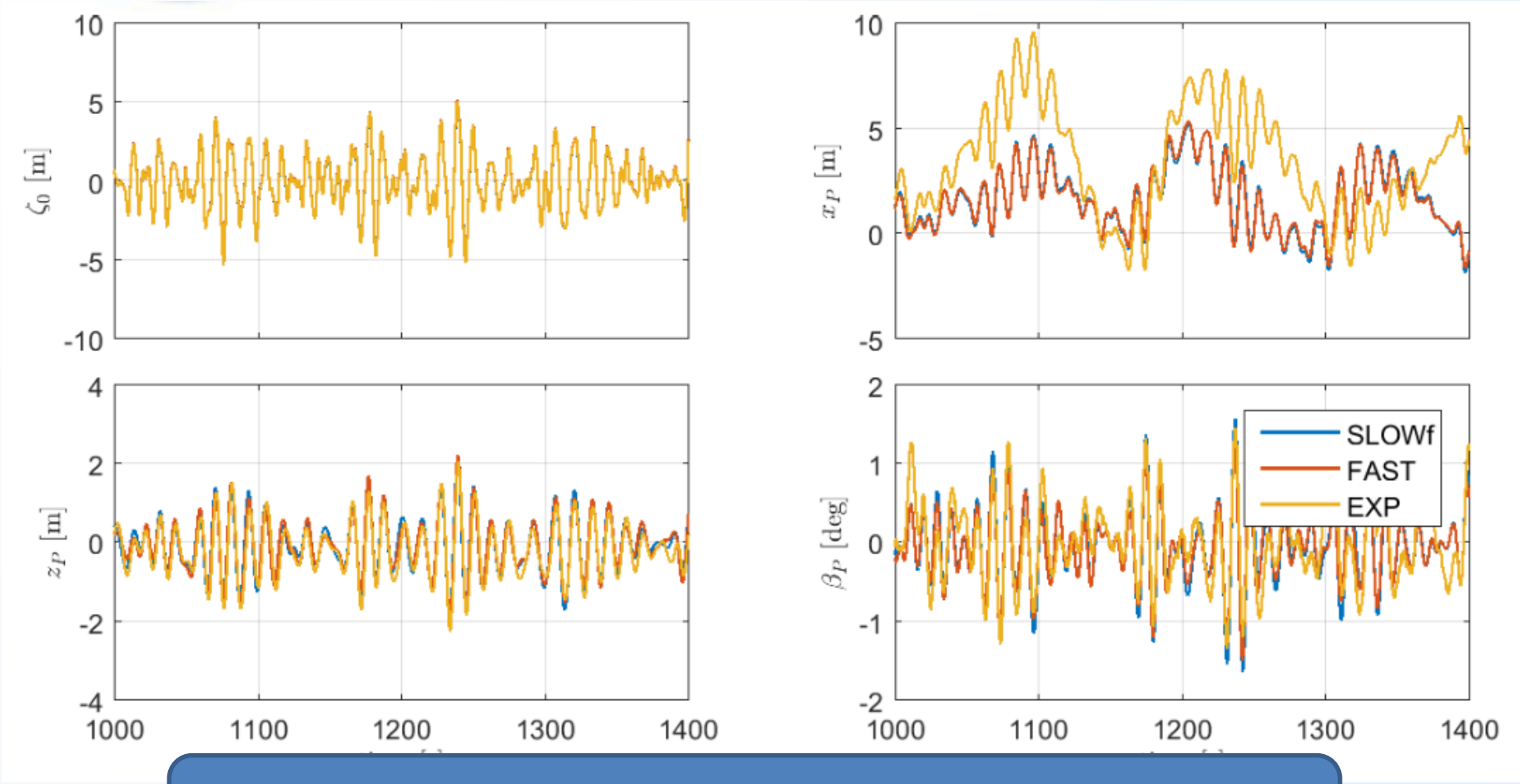
Simplified Low-Order Wind Turbine Model (SLOW)



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

LEMMER (2018)

Simplified Low-Order Wind Turbine Model (SLOW)



- Irregular waves, NAUTILUS-DTU10, good agreement between SLOW, FAST and experiment at SINTEF Ocean of LIFES50+

LIFES50+ D4.6

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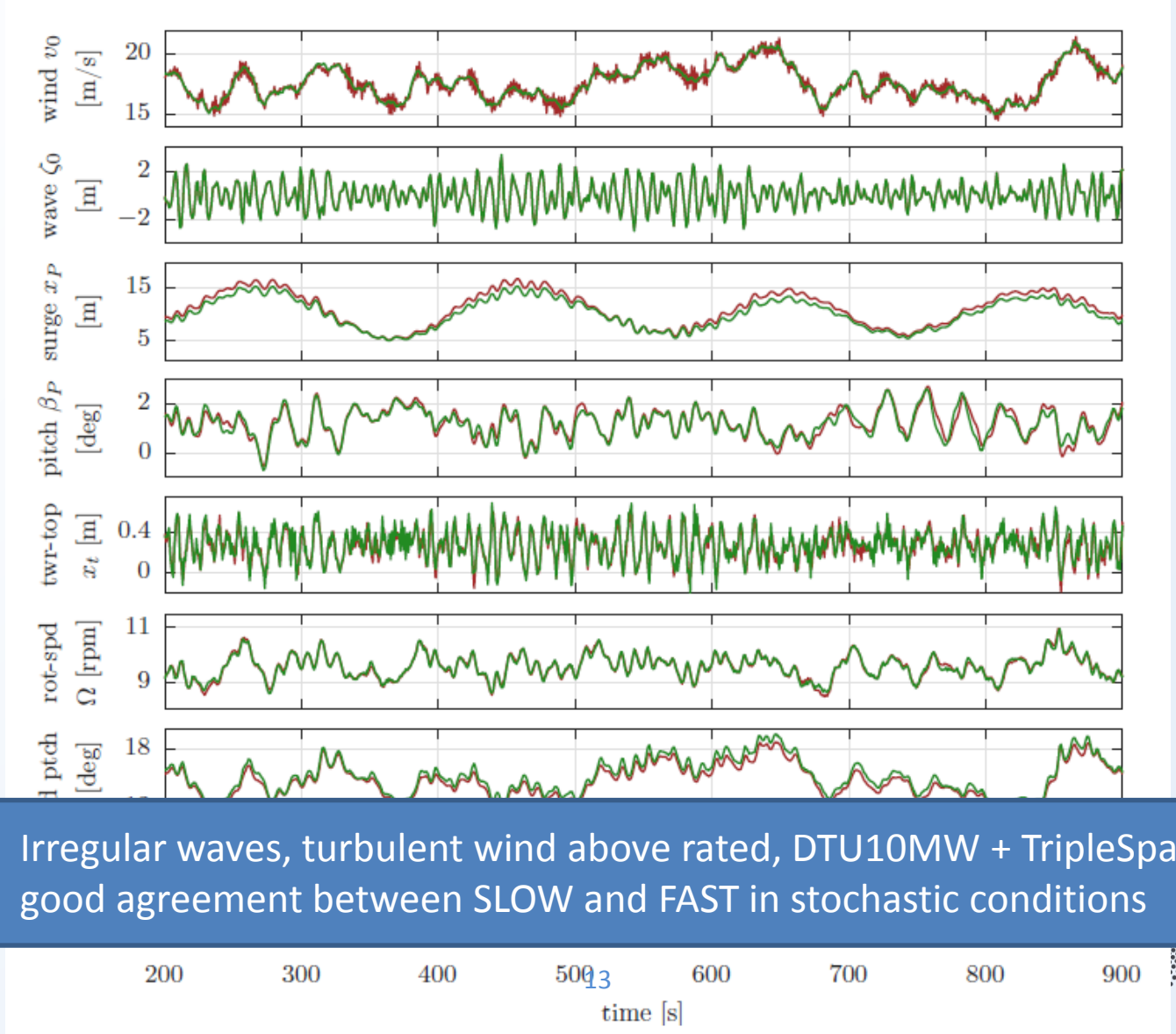
Simplified Low-Order Wind Turbine Model (SLOW)



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

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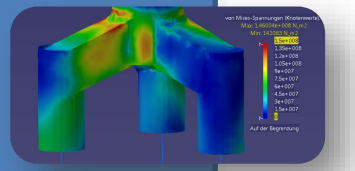
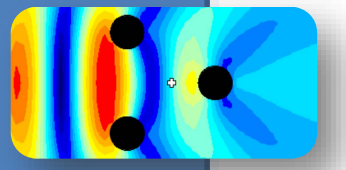
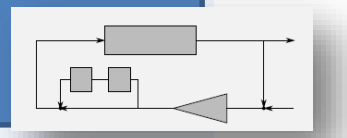
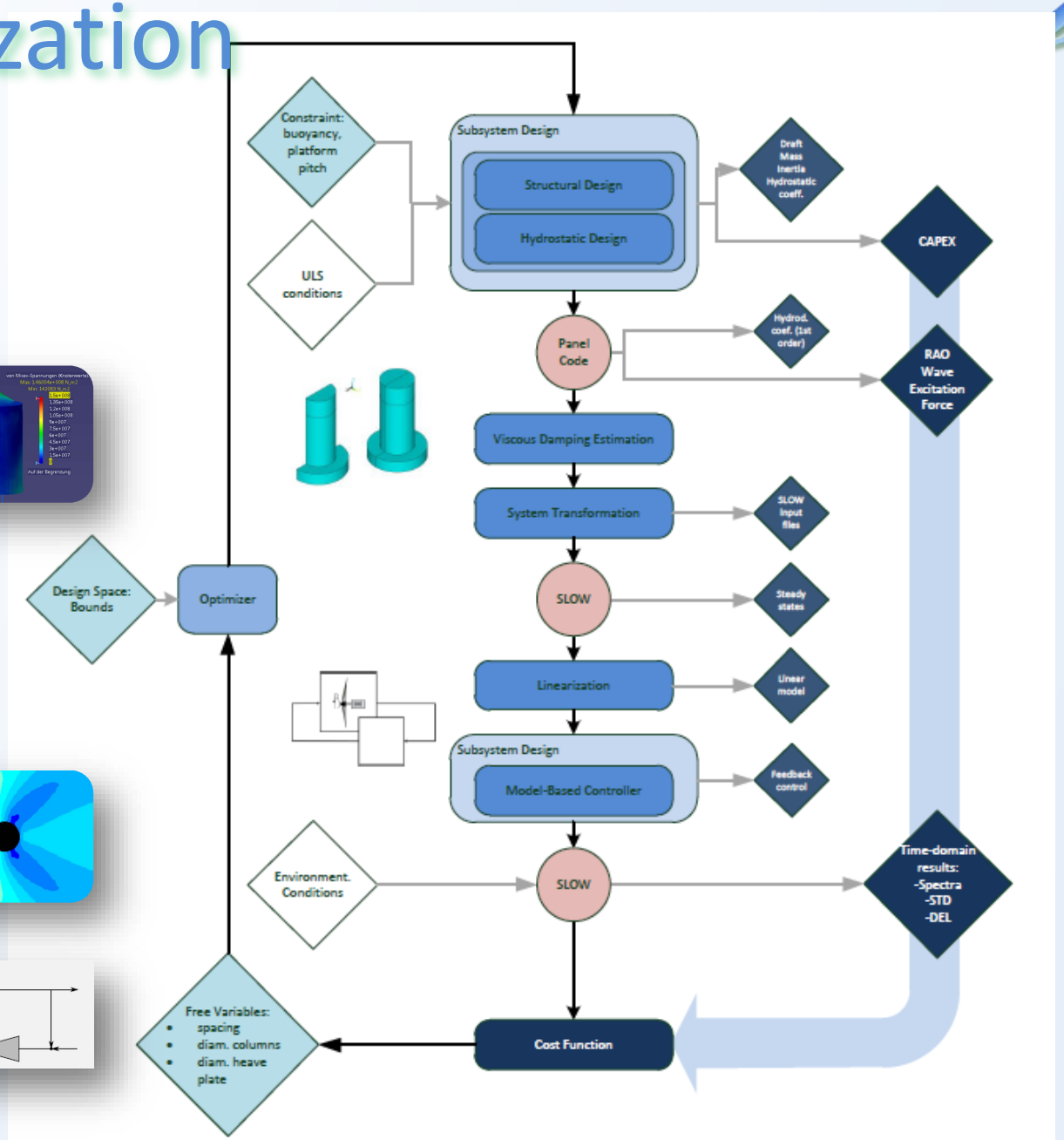
Integrated Optimization

- Parameterization of:
  - Steel design
  - Hydrostatics
  - Panel code
  - Controller



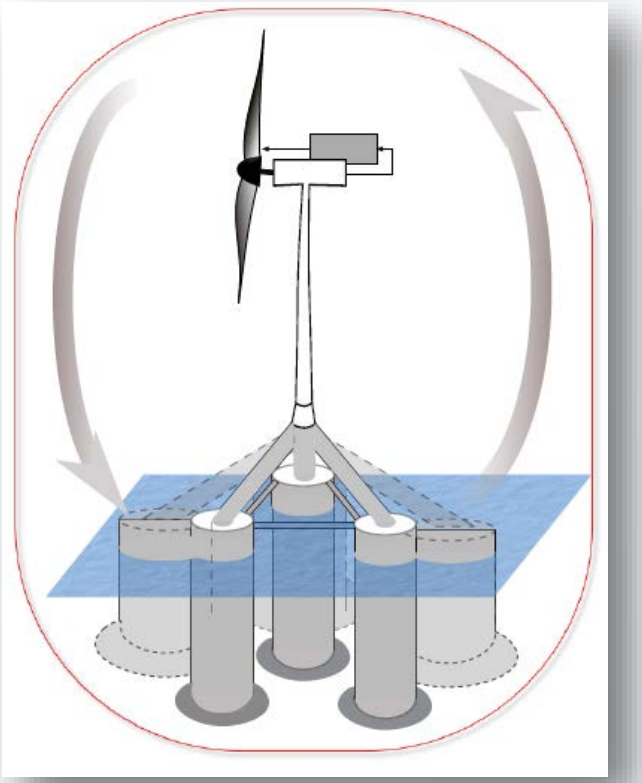




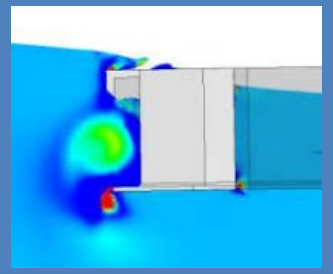


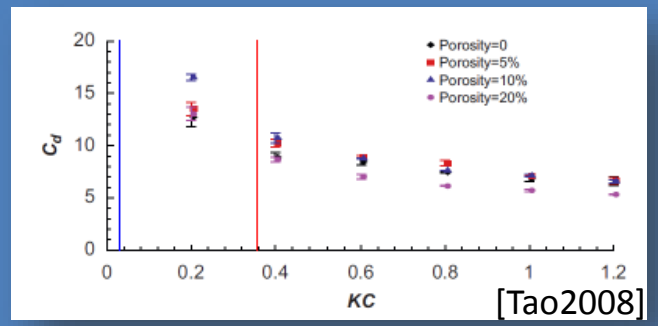
LIFES50+ D4.3

Integrated Optimization: Viscous Effects



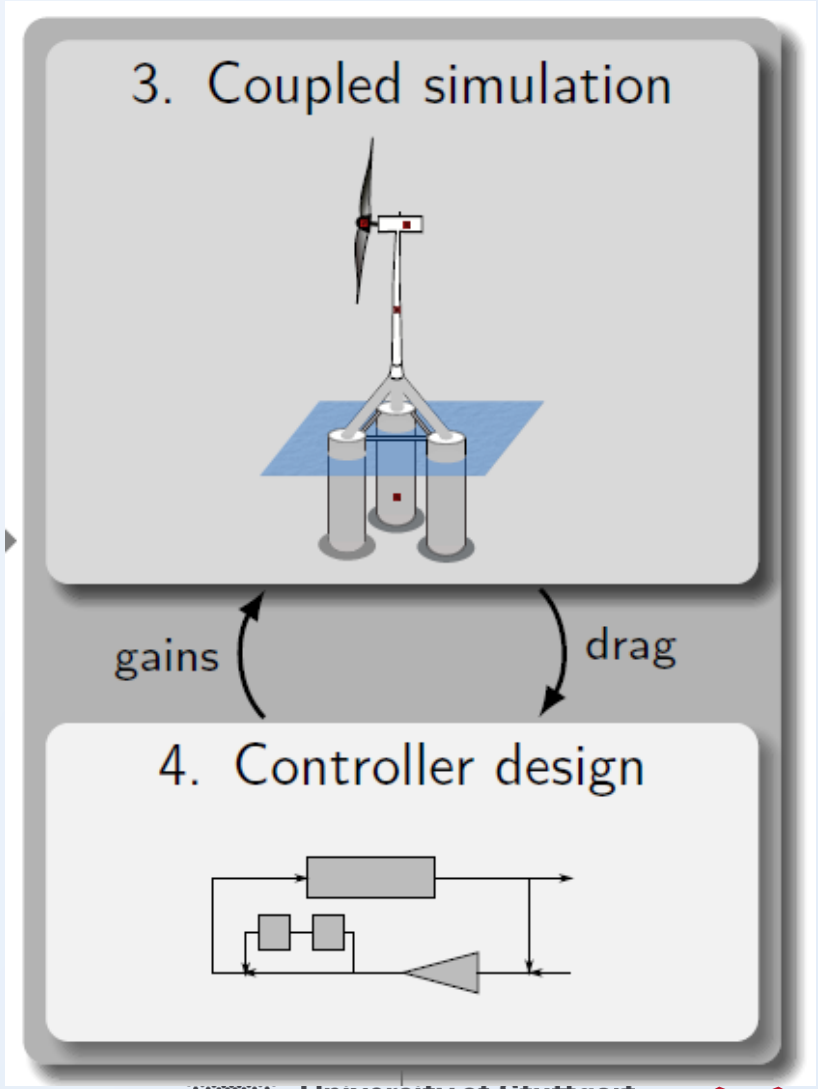
- Parametric hydrodynamic viscous drag





[Tao2008]

- Iterative controller tuning based on updated viscous drag coefficients



LIFES50+ D4.7

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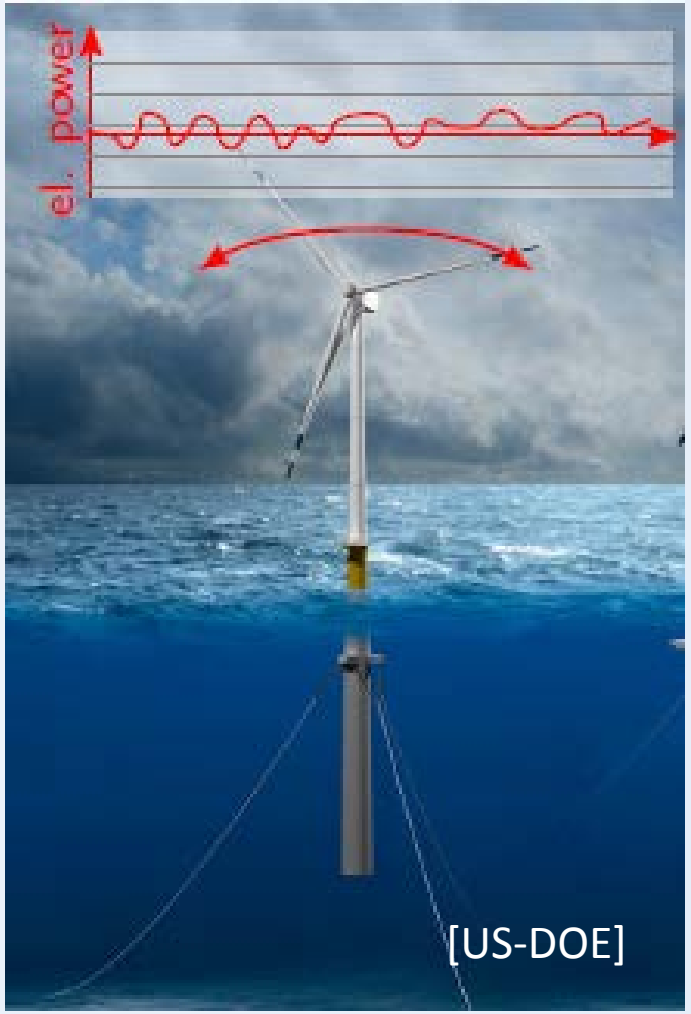
Integrated Optimization: Controller

- Automated controller design:
  - Determine stability limit at each operating point
  - Obtain robust gain scheduling, tailored to FOWT



Integrated Optimization: Controller

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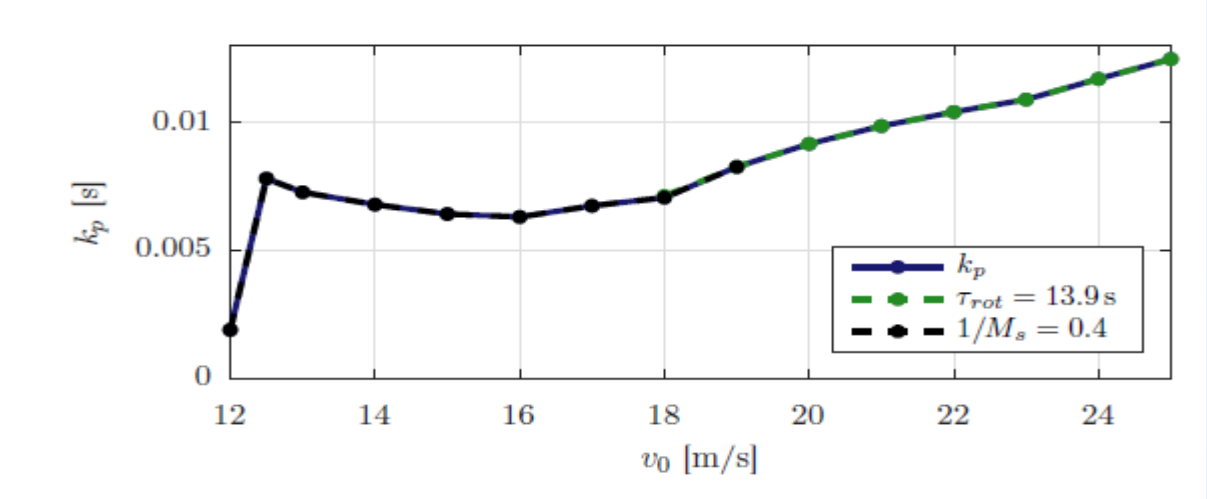
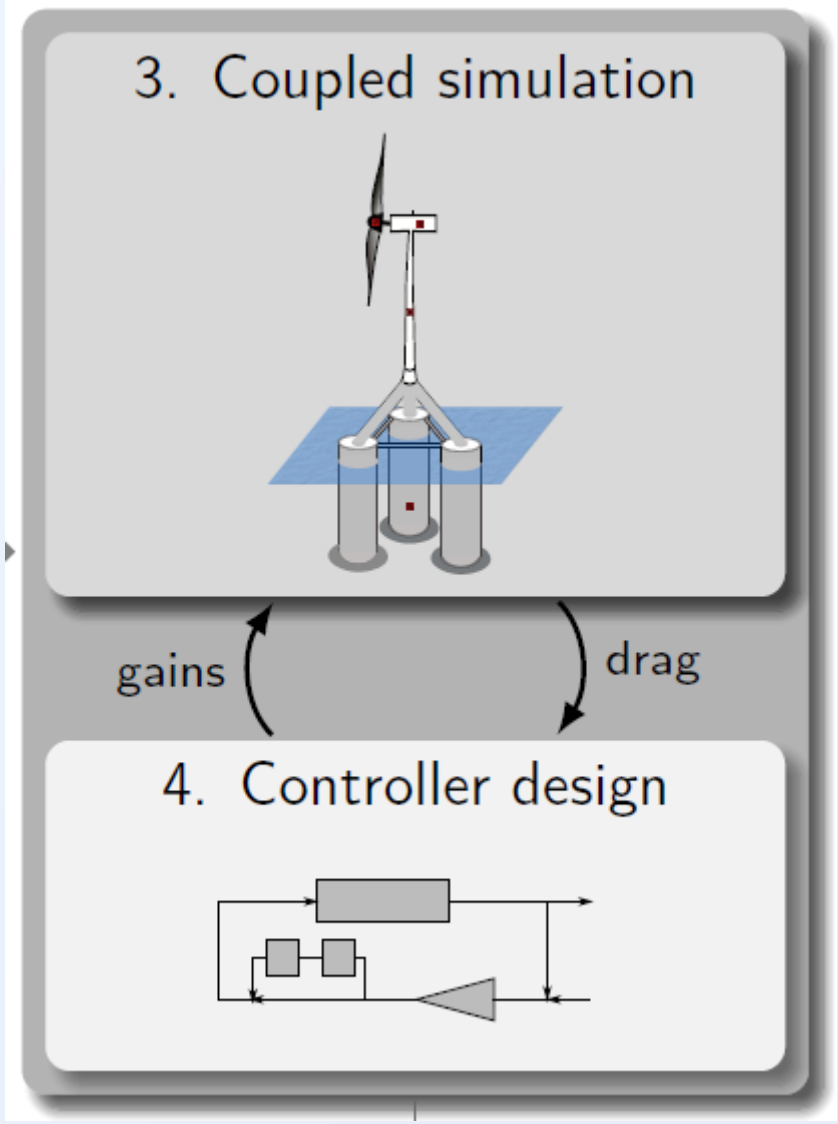




LEMMER (2018)

Integrated Optimization

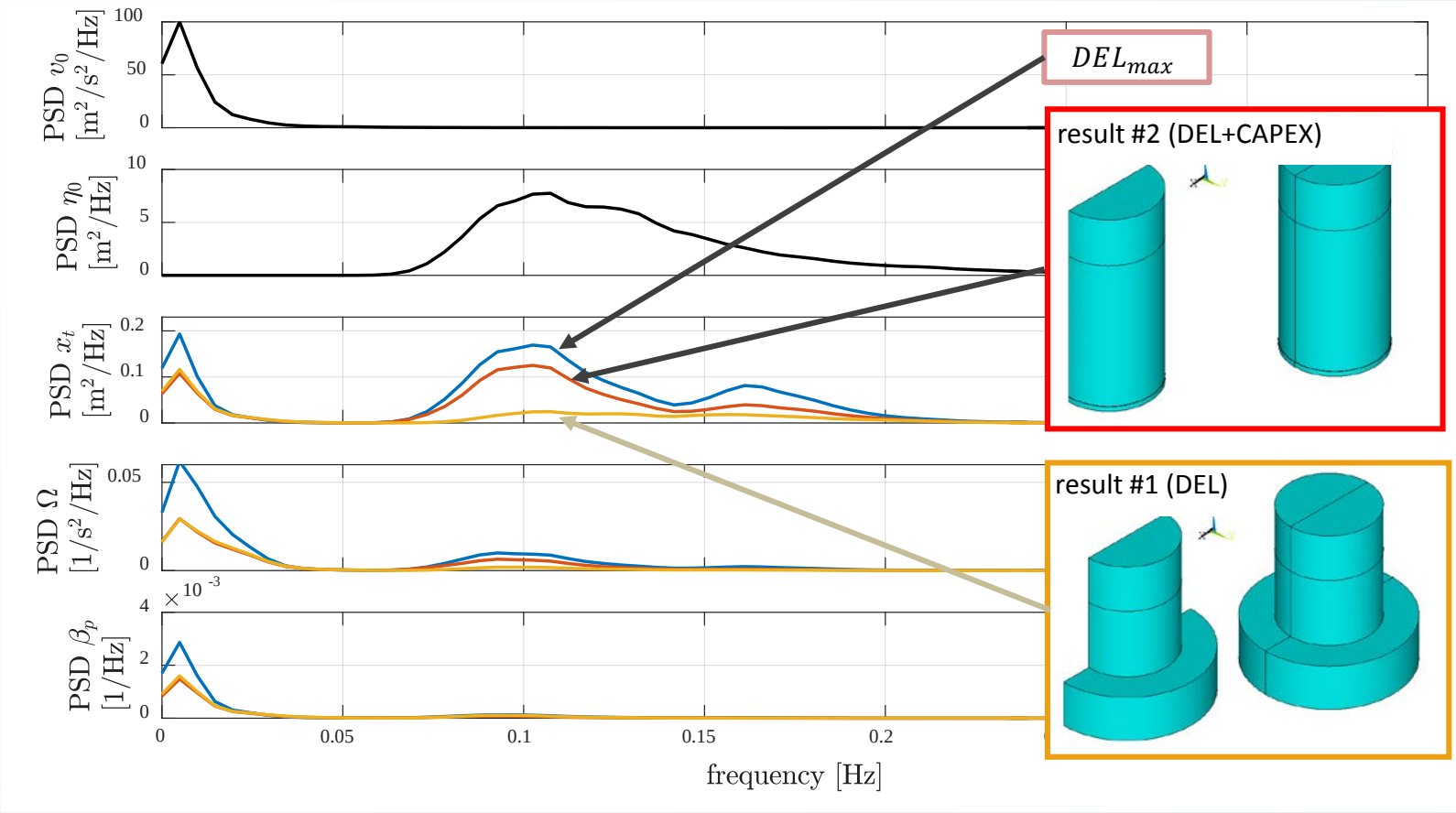
wind

waves

tower-top disp.

rotor speed

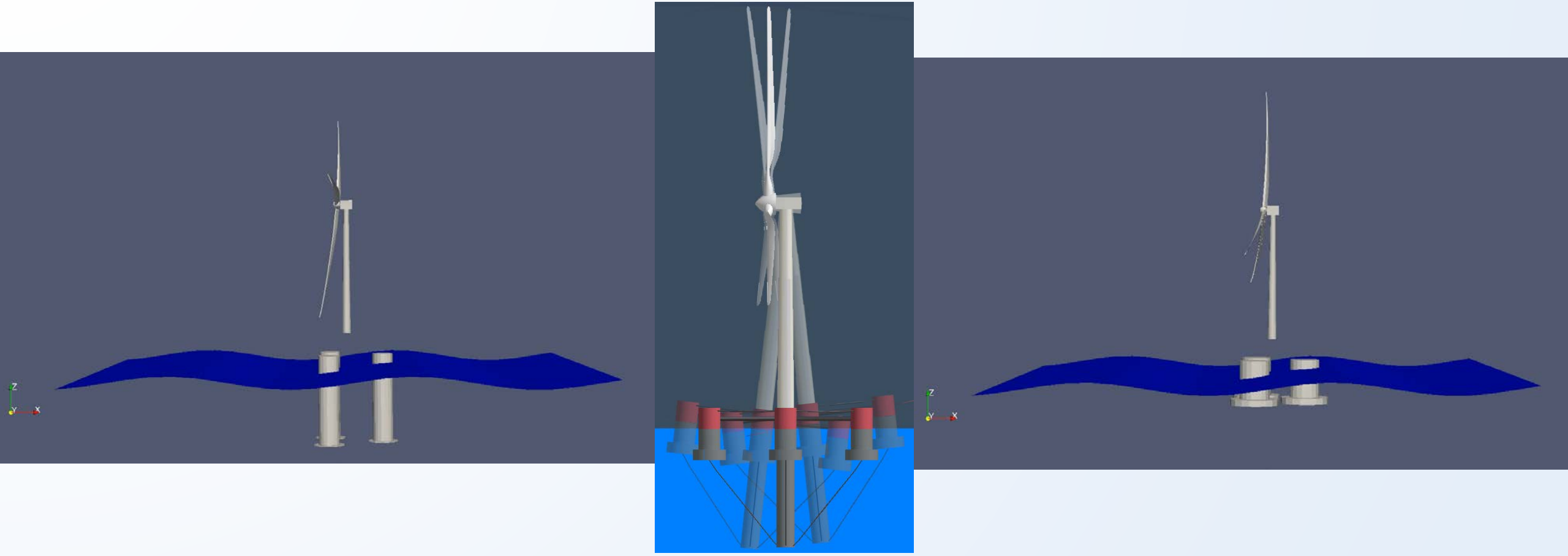
ptfm. pitch disp.



- Wave forces: Favorate harmonic response behavior through hull shape design
- Drift forces: Controller can damp slow-drift response

LEMMER (2017)

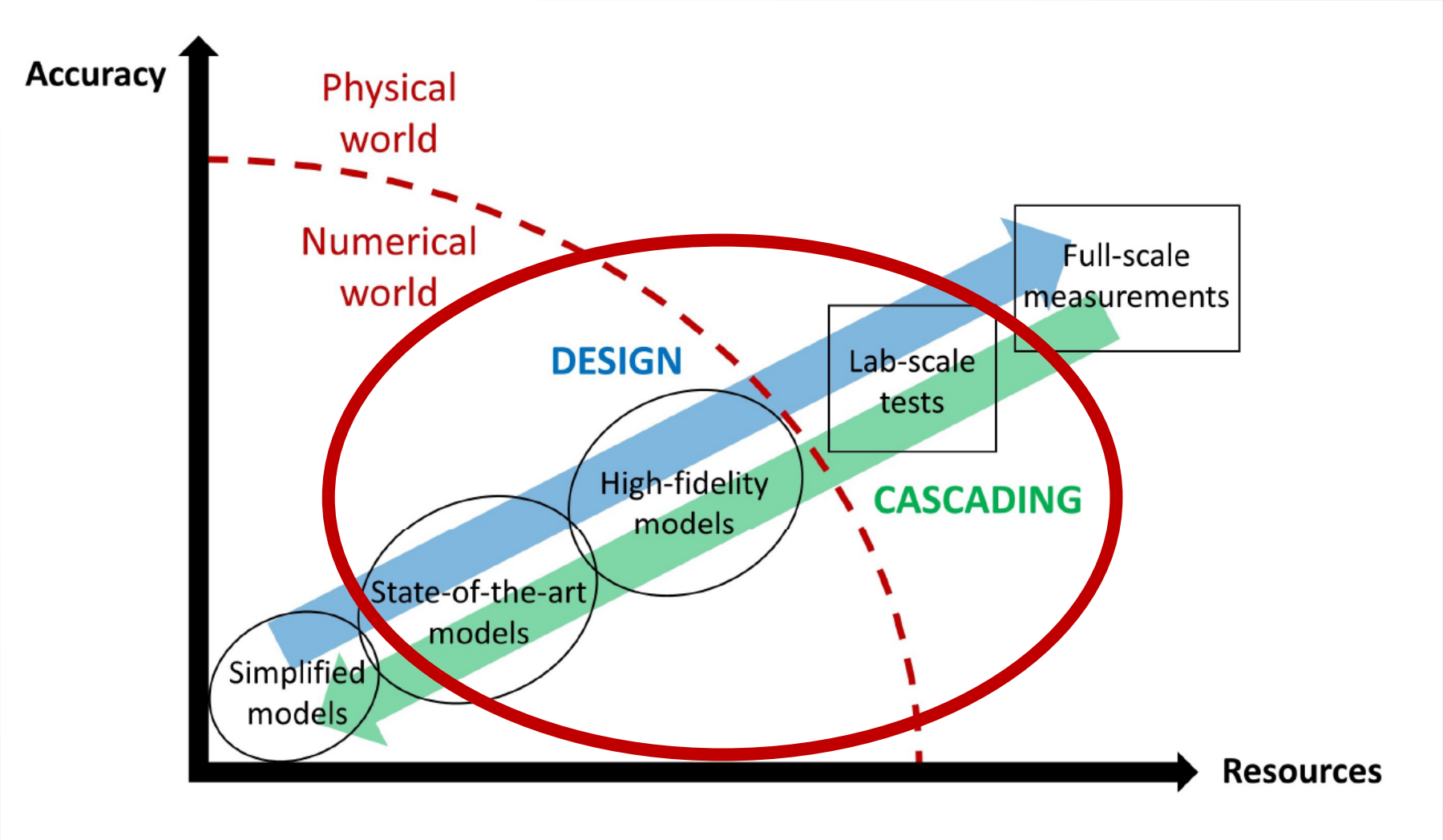
Integrated Optimization



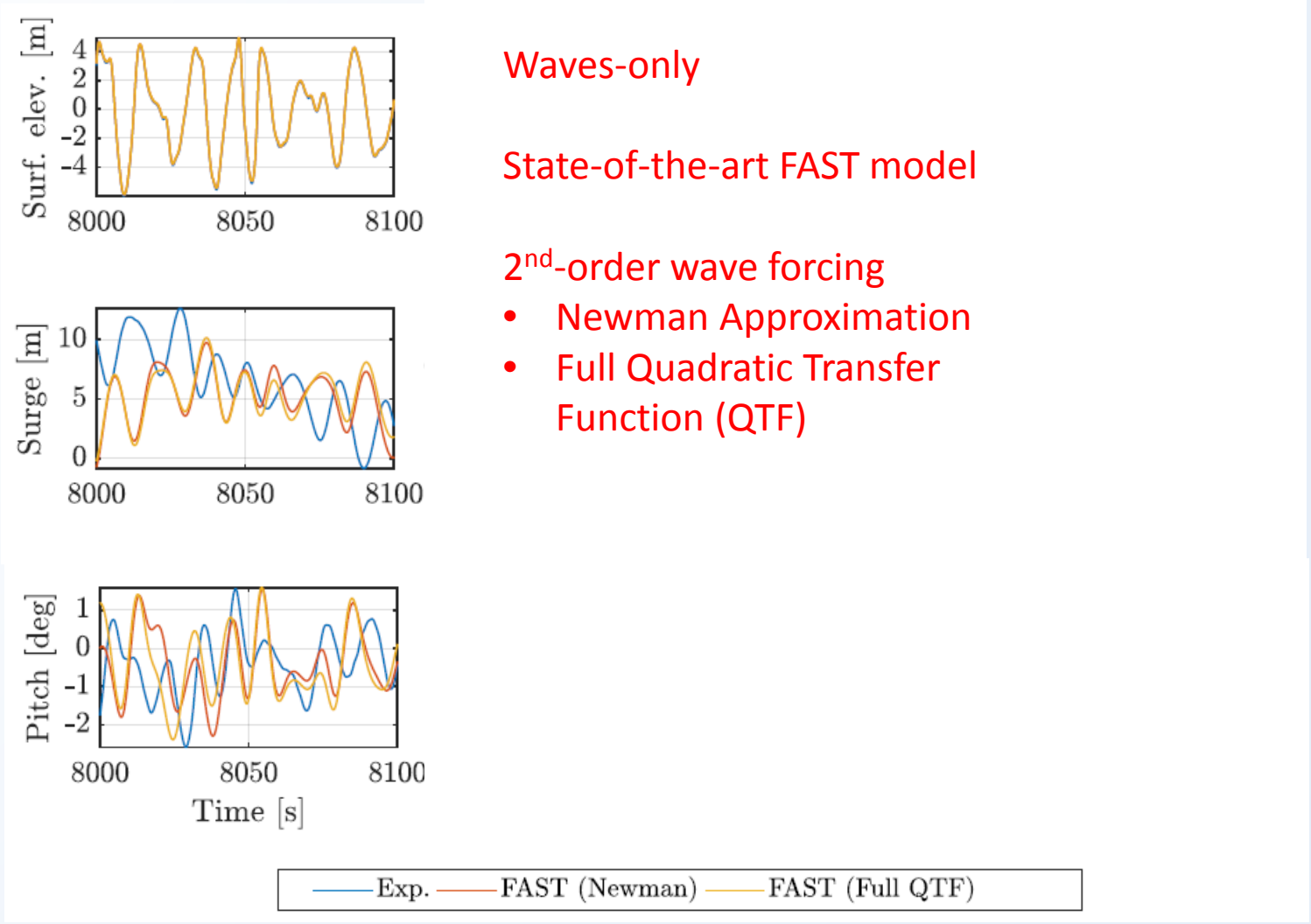
- Instantaneous center of rotation at hub through hull optimization
- No fore-aft motion from wave forcing

LEMMER (2019)

Model validation



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

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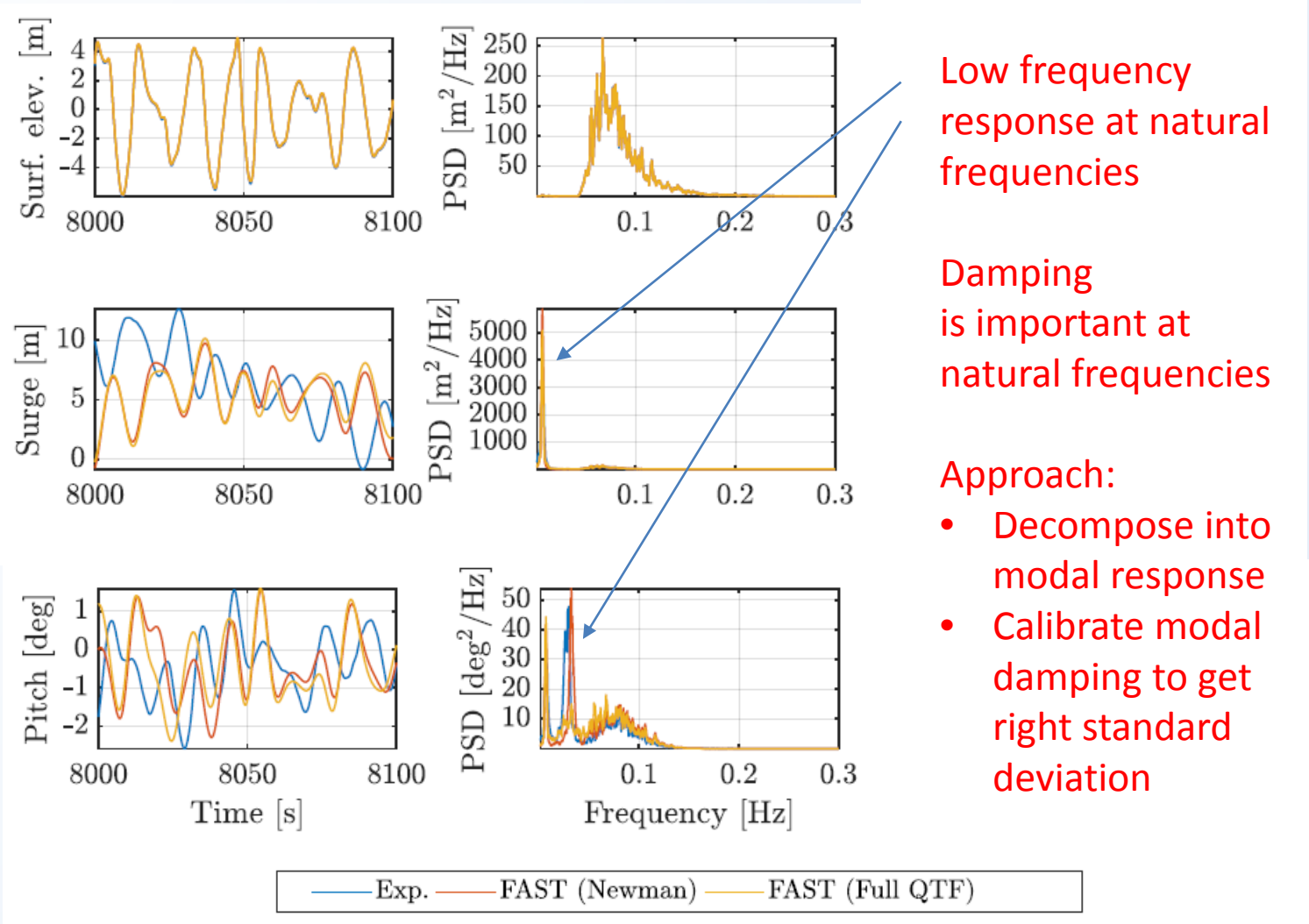
Extreme waves – Hs=10.9m Tp=15s



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)

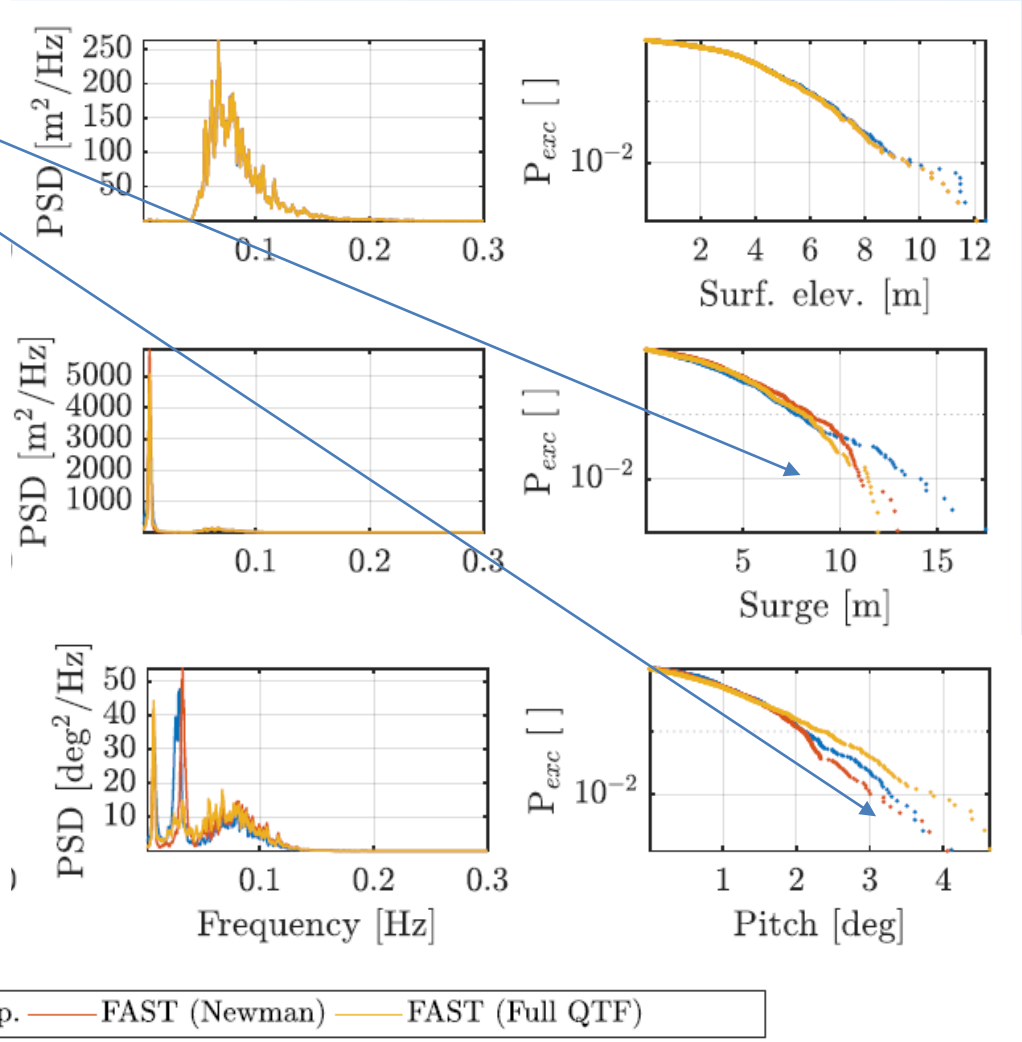
Extreme waves – Hs=10.9m Tp=15s

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)?



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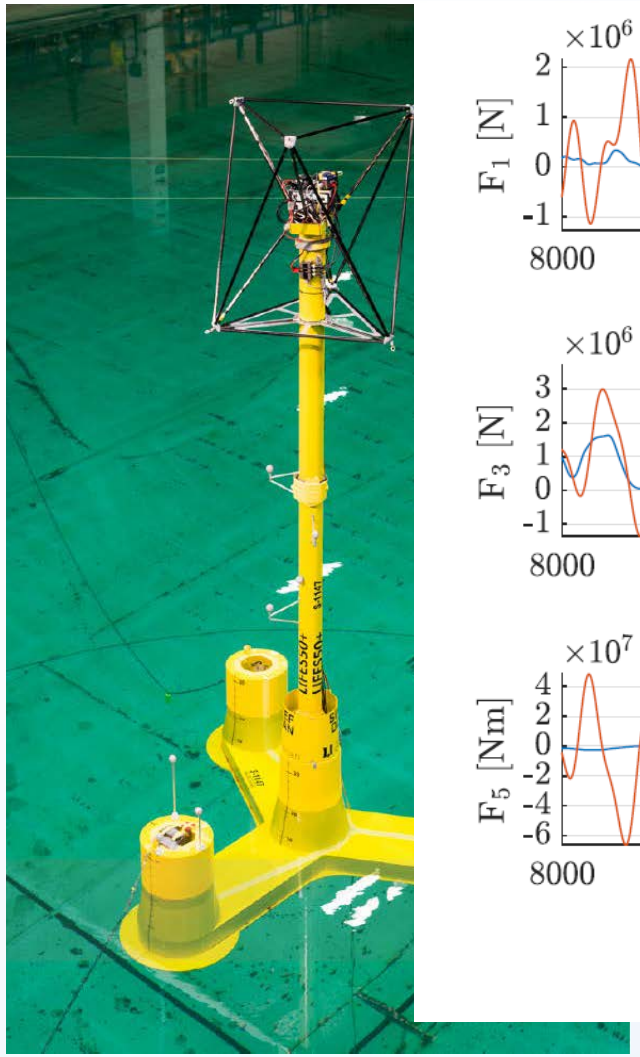
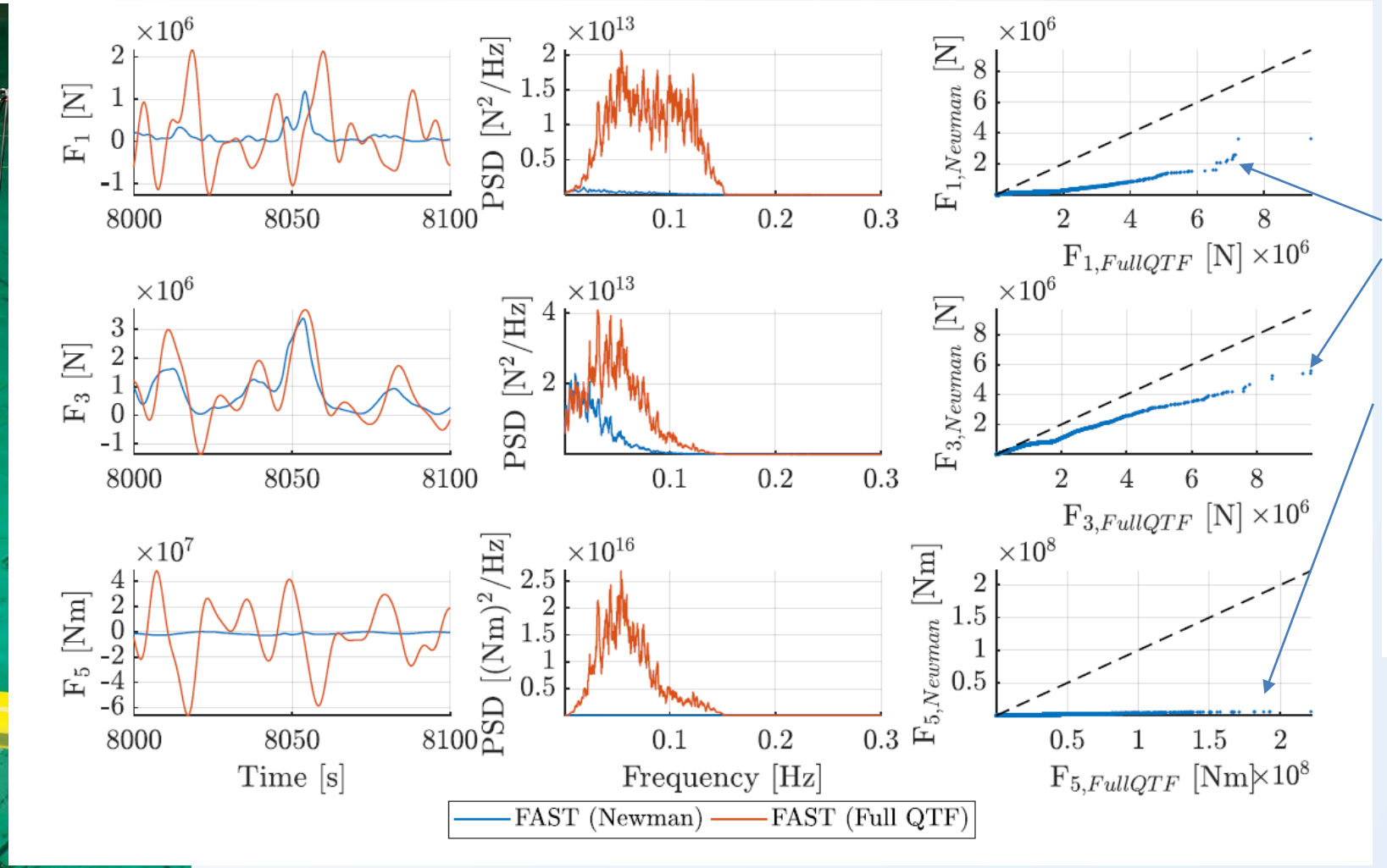
Accuracy of Newman approximation





Newman approximation under-predicts

- Notably for surge and heave
- Strongly for pitch

Calibration can help. But a test is then required.

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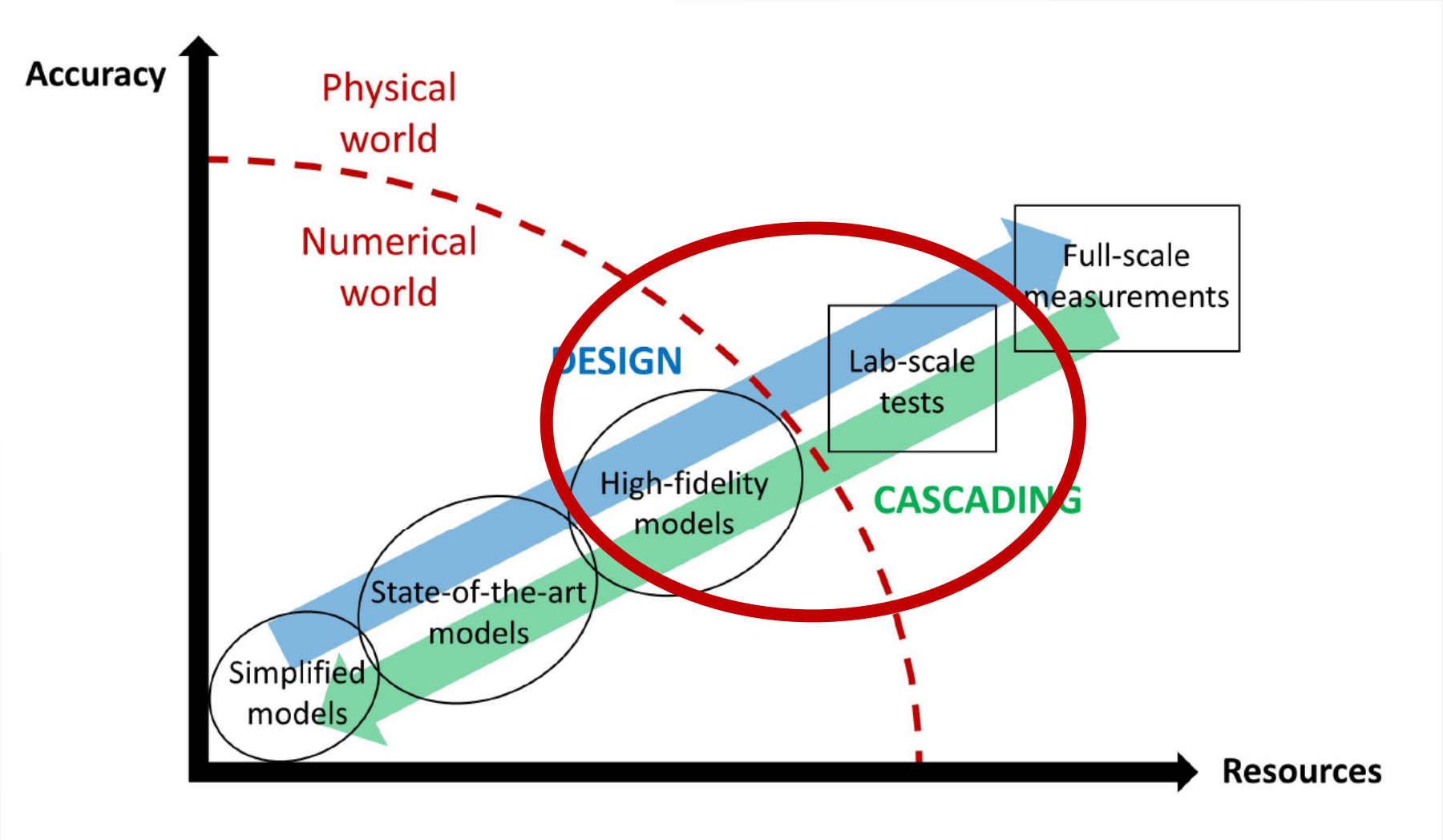
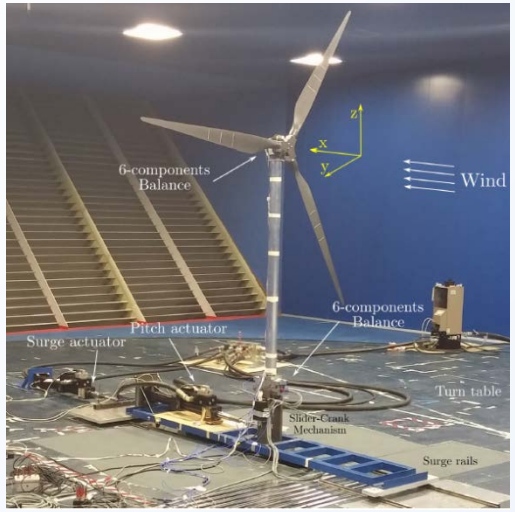
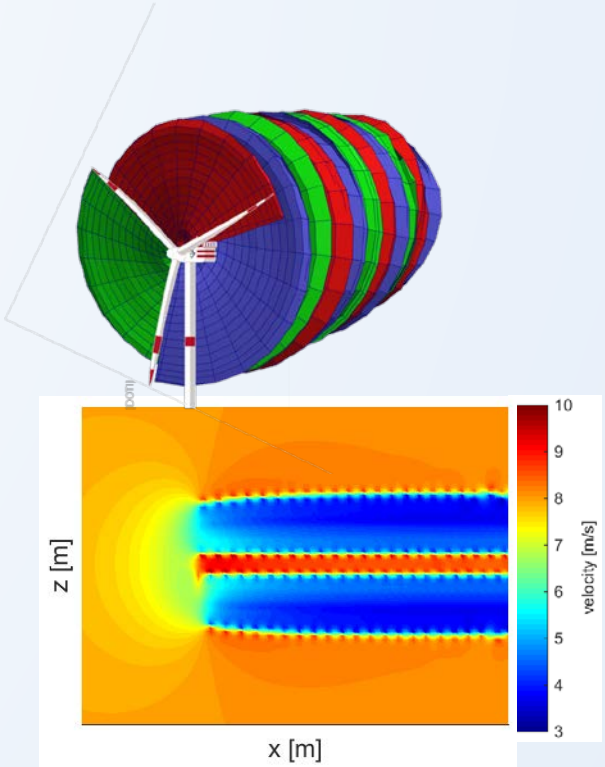
Advanced models



Advanced modelling: Free wake aerodynamics



Experimental studies in windtunnel by Polimi



Simulation using a lifting line/free vortex approach

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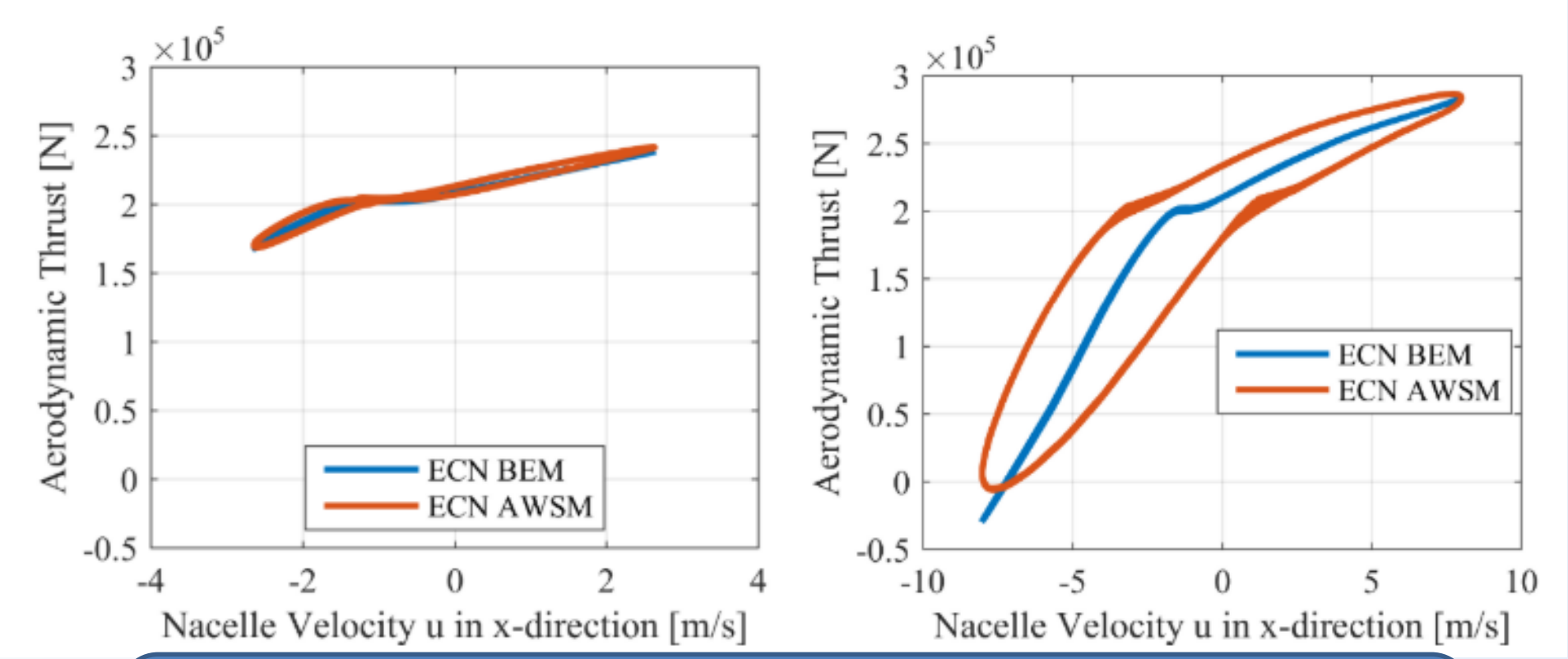
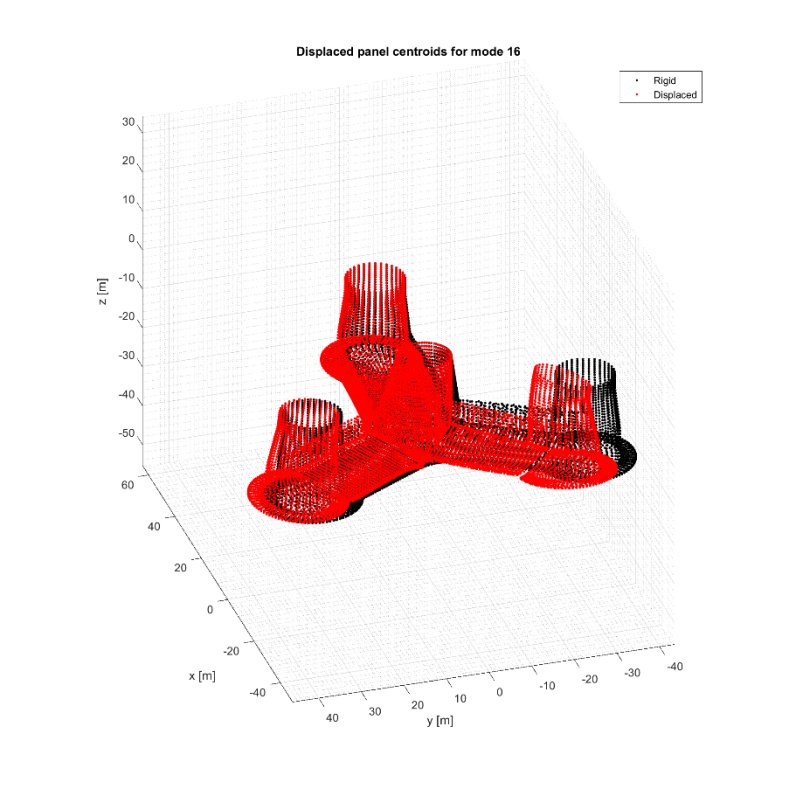
Advanced modelling: Free wake aerodynamics



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

LIFES50+ D4.8

Modelling of floater flexibility



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

- Borg, Hansen & Bredmose (2016, 2017, 2019)

Theoretical background

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

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

Added mass **Damping** **Restoring**

External forces:
-wave excitation
-wind turbine loads
-mooring

– Rigid: 6 DOF body motion is considered

– Easily extended to include *N* flexible modes such that **q** contains (*6+N*) states

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

$$\frac{\partial \phi_j}{\partial n} = i\omega n_j$$

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

- Borg, Hansen & Bredmose (2016, 2017, 2019)

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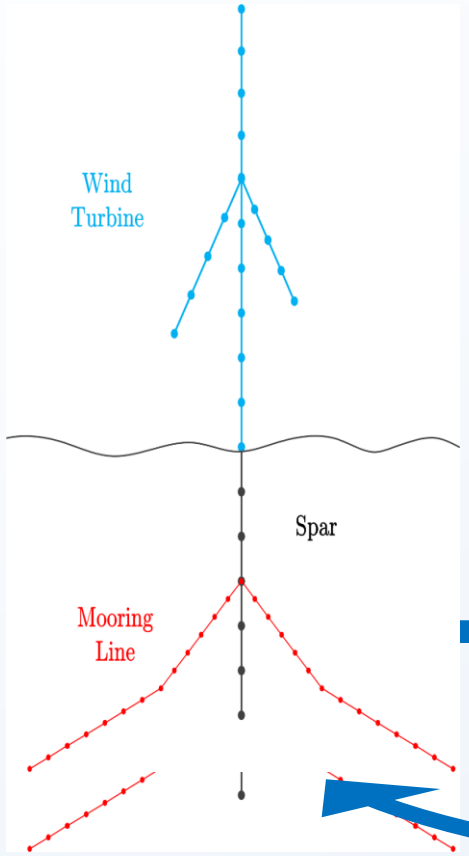
Methodology

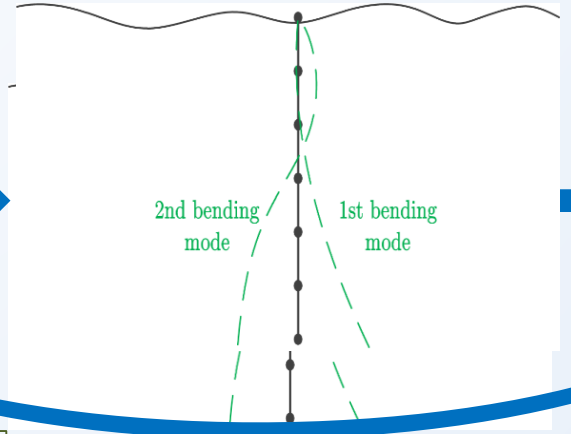
$$\left(\tilde{\mathbf{M}}+\tilde{\mathbf{A}}_{\infty}\right)\ddot{\mathbf{q}}(t)+\tilde{\mathbf{C}}\dot{\mathbf{q}}(t)+\int_0^t \tilde{\mathbf{L}}(t-\tau)\,\dot{\mathbf{q}}(\tau)d\tau+\left(\tilde{\mathbf{K}}+\tilde{\mathbf{K}}_h\right)\mathbf{q}(t)=\tilde{\mathbf{f}}_D(t)+\tilde{\mathbf{f}}_{con}(t)$$

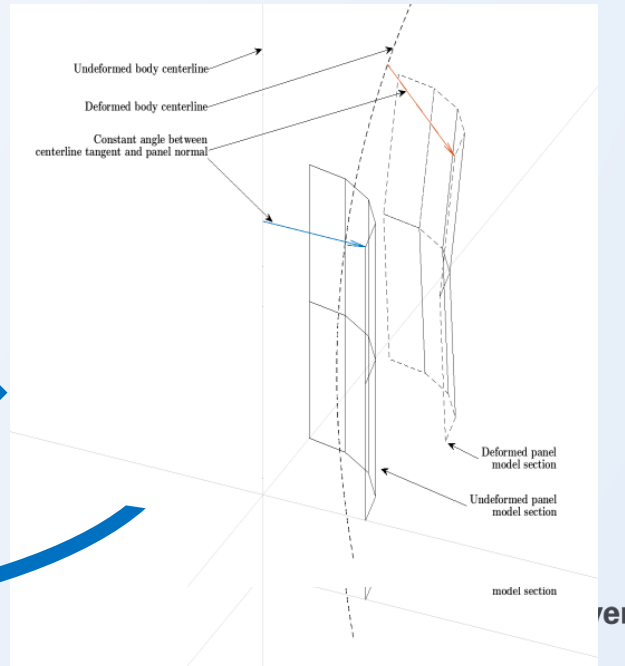
HAWC2

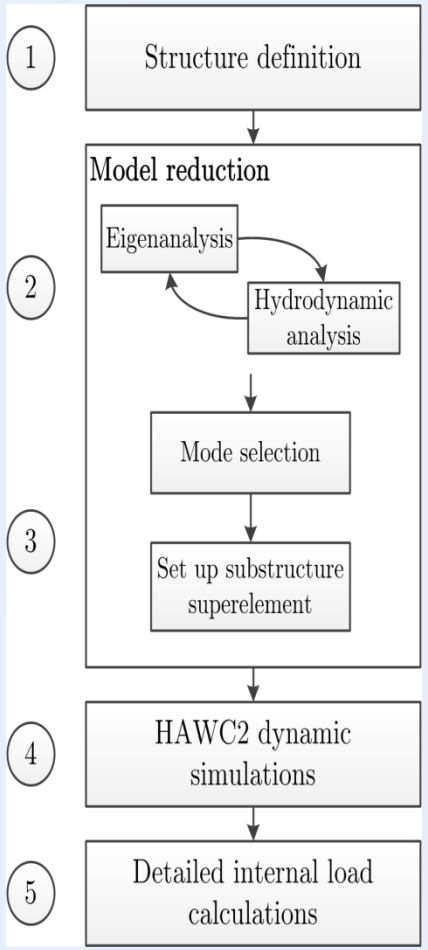
HAWC2
WAMIT

Engineer
HAWC2



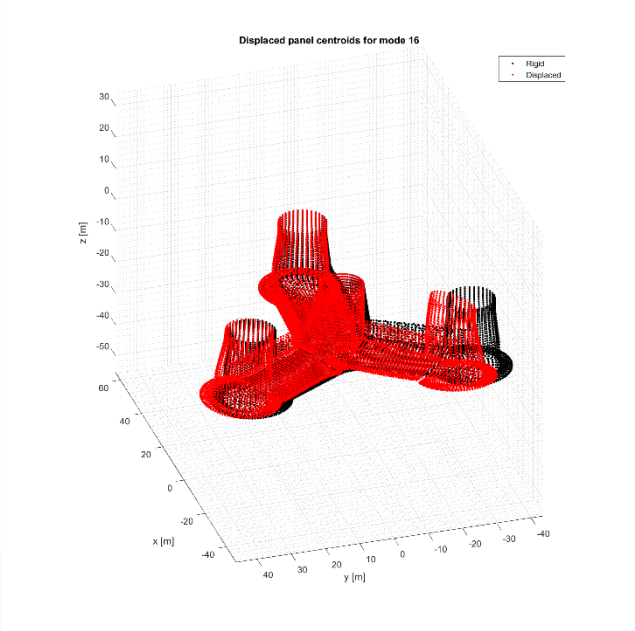


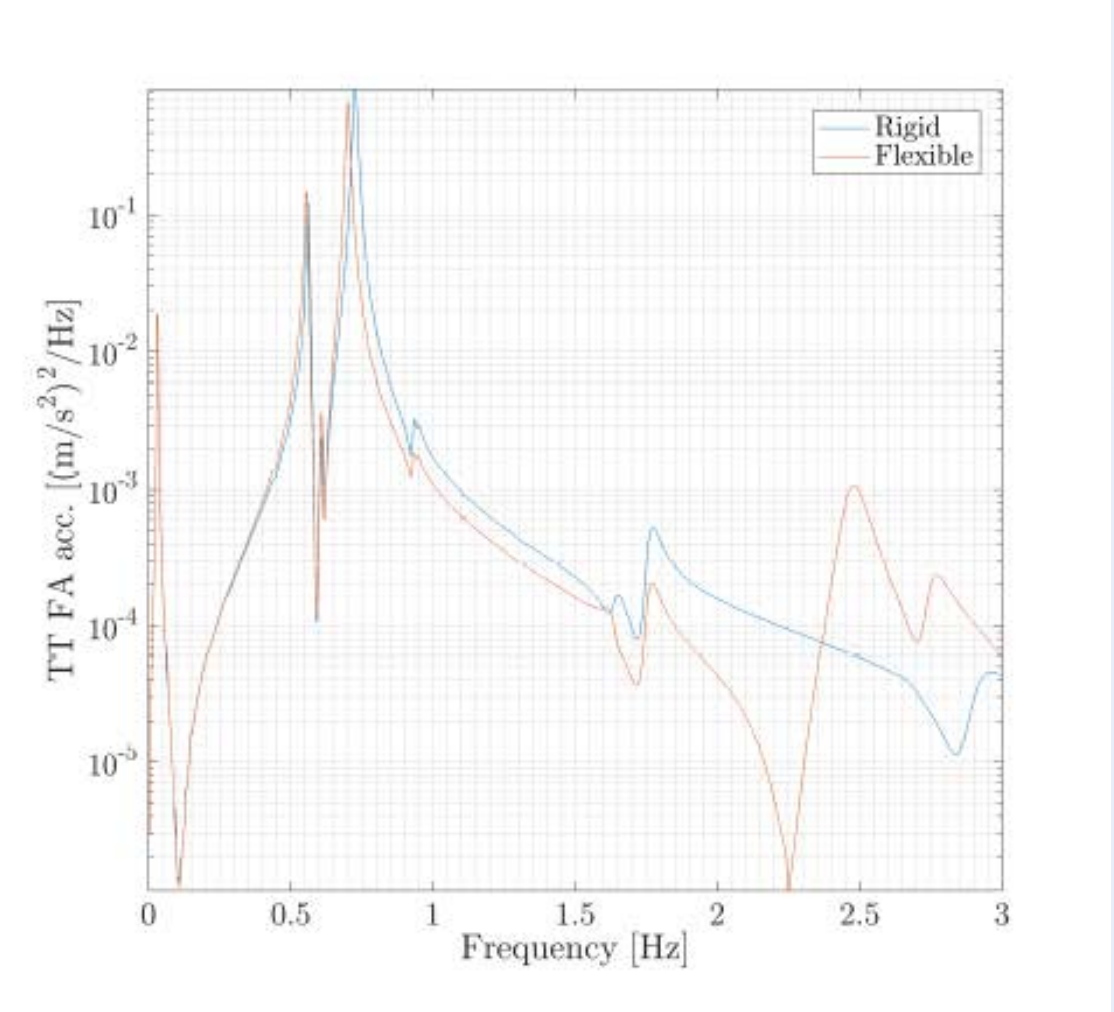




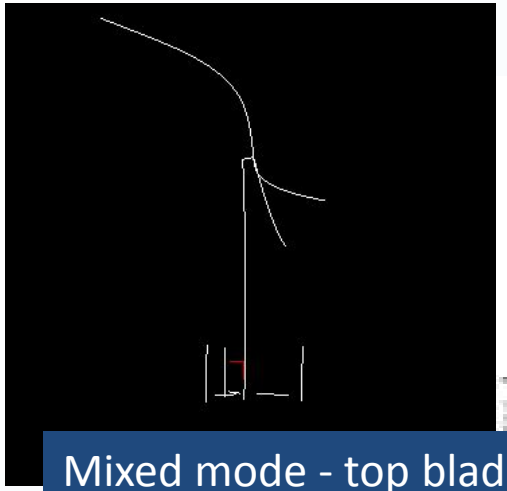
- Borg, Hansen & Bredmose (2016, 2017, 2019)

Example: OO floater in DTUs HAWC2 model

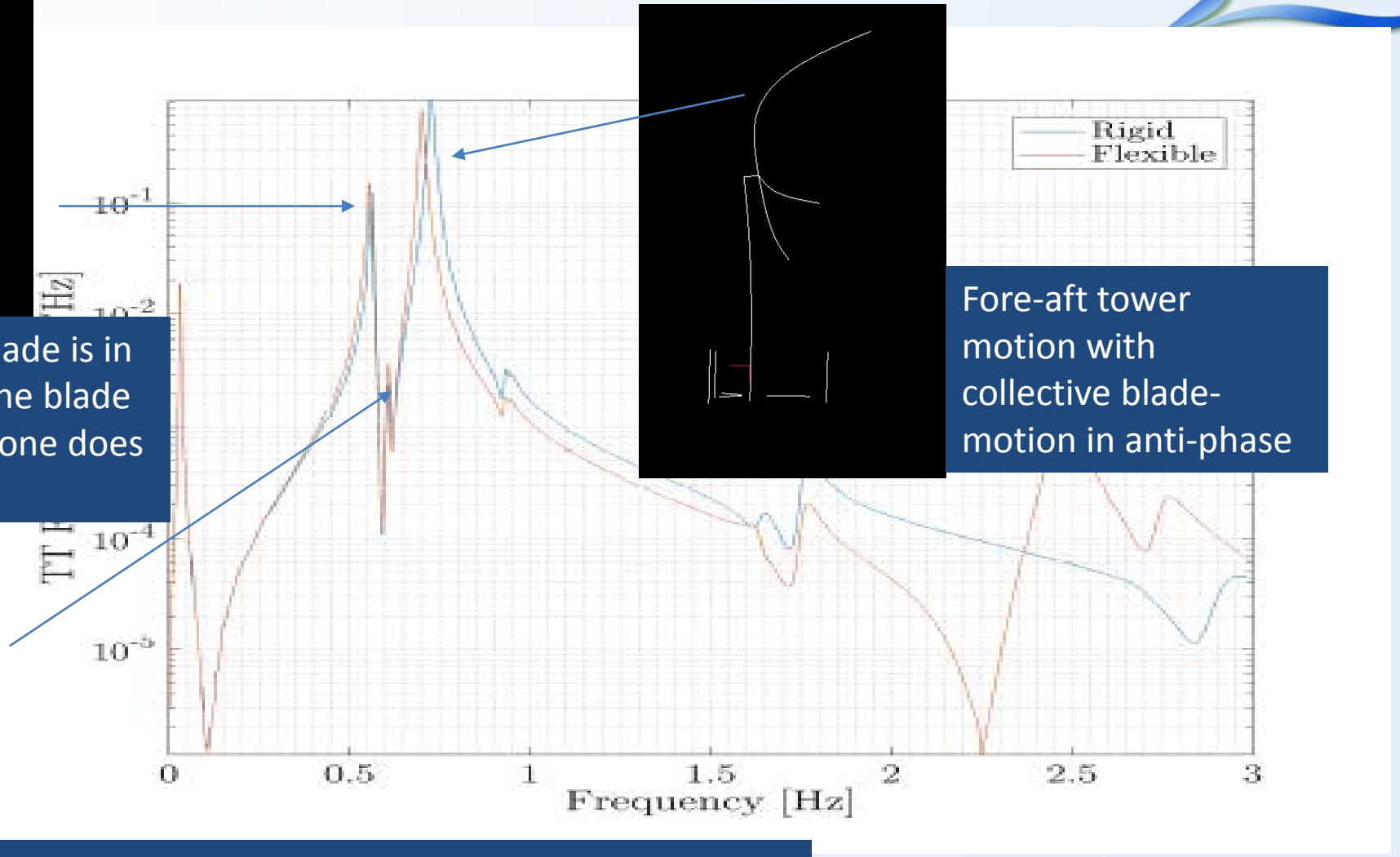




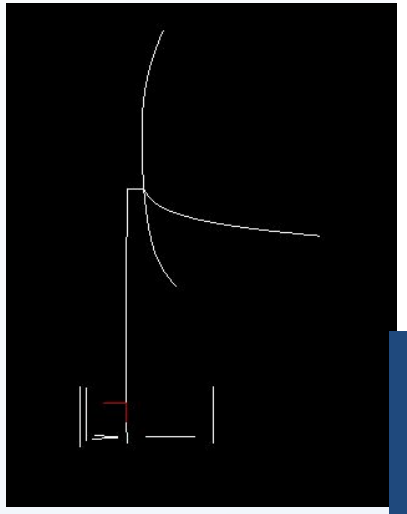
- Borg, Hansen & Bredmose (2016, 2017, 2019)



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

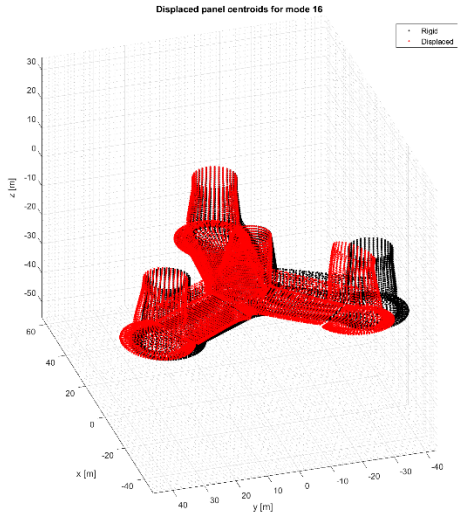


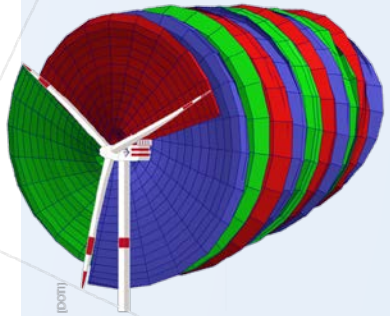
Fore-aft tower motion with collective blade-motion in anti-phase



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

Wrap up





Lab-scale tests

High-fidelity models

State-of-the-art models

Simplified models

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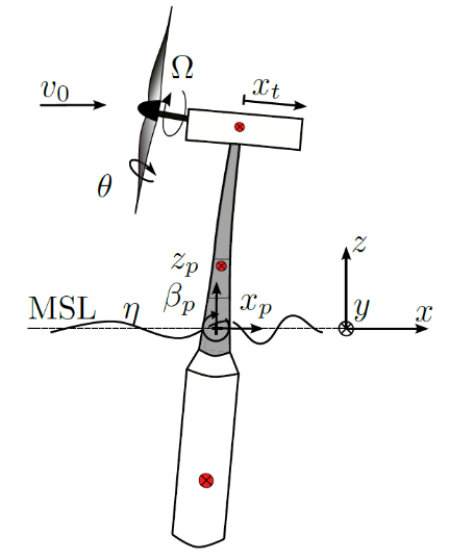

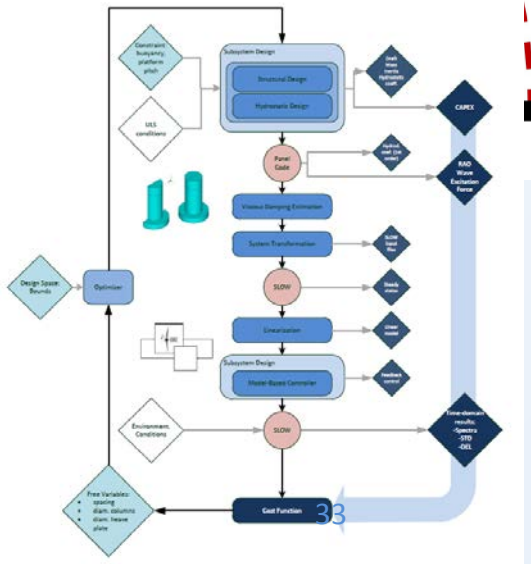

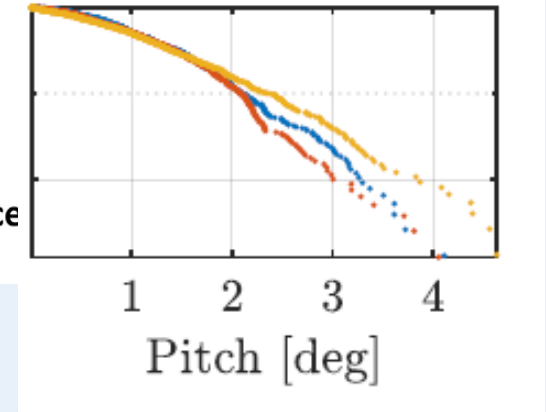

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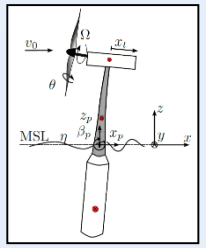
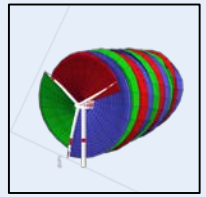
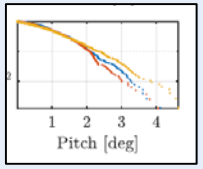
Research needs

- 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







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Publications on simplified models

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

- Journal paper: Antonio Pegalajar-Jurado, Michael Borg, and Henrik Bredmose 'An efficient frequency-domain model for quick load analysis of floating offshore wind turbines.' Wind Energy Science **3**, pp 693-712 2018.
- Journal paper: Frank Lemmer, Wei Yu and Po Wen Cheng (2018) 'Iterative Frequency-Domain Response of Floating Offshore Wind Turbines with Parametric Drag' J. Mar. Sci. Eng. 2018, **6**, 118.
- Journal paper: Madsen, Pegalajar-Jurado and Bredmose (2019, in submission) 'Performance study of the QuLAF pre-design model for a 10MW floating wind turbine'. Overview presented as poster at EERA DeepWind 2019.
- Paper and poster for EERA DeepWind 2016: Pegalajar-Jurado, Bredmose & Borg (2016) 'Multi-level hydrodynamic modelling of a 10MW TLP wind turbine' Energy Procedia **94**, pp 124-132
- Paper and poster at EERA DeepWind 2016: Lemmer, F., Raach, S., Schlipf, D., & Cheng, P. W. (2016). 'Parametric Wave Excitation Model for Floating Wind Turbines'. Energy Procedia **94**, pp 290-305.
- Paper at Torque 2016: Lemmer, F., Schlipf, D., & Cheng, P. W. (2016). ´Control design methods for floating wind turbines for optimal disturbance rejection', J. Phys. Conf. Series **753**
- Paper at OMAE2017: Lemmer, Müller, Yu, Schlipf and Cheng (2017) "Optimization of floating offshore wind turbine platforms with a self-tuning controller" ASME 2017.
- Paper at OMAE 2018: F. Lemmer, P.W. Cheng, Y. Wei, A. Pegalajar-Jurado, M. Borg, R.F. Mikkelsen and H. Bredmose 'The TripleSpar Campaign: Validation of a reduced-order simulation model for floating wind turbines'. ASME 2018.
- Paper and presentation at EERA DeepWind 2019: Frank Lemmer, Wei Yu, Kolja Müller, Po Wen Cheng (2019) 'Wave Cancelling SemiSubmersible Design for Floating Offshore Wind Turbines'.

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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

- Paper at EERA DeepWind 2018: Antonio Pegalajar-Jurado, Henrik Bredmose, Michael Borg, Jonas G. Straume, Trond Landbø, Haakon S. Andersen, Wei Yu, Kolja Müller and Frank Lemmer (2018) 'State-of-the-art model for the LIFES50+ OO-Star Wind Floater Semi 10MW floating wind turbine'. J. Phys. Conf. Series. **1104** 2018.

- Public models available at DTUs GitLab site https://rwt.windenergy.dtu.dk/dtu10mw/dtu-10mw-rwt/tree/master/aeroelastic_models/fast.

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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
- Journal paper: M Borg, AM Hansen and H Bredmose (2019) 'Elasticity of floating offshore wind support structures in dynamic calculations'. Submitted.
- Journal paper: Pegalajar-Jurado, A. and Bredmose, H (2019) 'Reproduction of slow-drift motions of a floating wind turbine using second-order hydrodynamics and Operational Modal Analysis'. To appear in *Marine Structures*.
- Paper for Torque 2016: Borg, Hansen and Bredmose (2016) 'Floating substructure flexibility of large-volume 10MW offshore wind turbine platforms' J. Phys. Conf. Series. **753** 2016.
- Paper for OMAE2017: Borg, Hansen and Bredmose (2017) "Elastic deformations of floaters for offshore wind turbines: Dynamic modelling and sectional load calculations"
- Paper for OMAE2017: Pegalajar-Jurado, Borg, Robertson, Jonkman and Bredmose (2017) "Effect of second-order and fully nonlinear kinematics on a TLP wind turbine in extreme wave conditions"
- Poster at EERA DeepWind 2018: H.S. Chivaee, M. Borg, A. Pegalajar-Jurado and H. Bredmose (2018) 'A CFD model for the LIFES50+ OO-Star Wind Floater Semi 10MW'.
- Paper and presentation at 21st Australasian Fluid Mechanics Conference, Adelaide, Australia 2018: Sarlak Chivaee, H., Pegalajar Jurado, A. M., & Bredmose, H. (2018). 'CFD Simulations of a Newly Developed Floating Offshore Wind Turbine Platform using OpenFOAM'.
- PhD Thesis: F. Lemmer (2018). *Low-Order Modeling, Controller Design and Optimization of Floating Offshore Wind Turbines*. University of Stuttgart. ISBN 978-3-8439-3863-1

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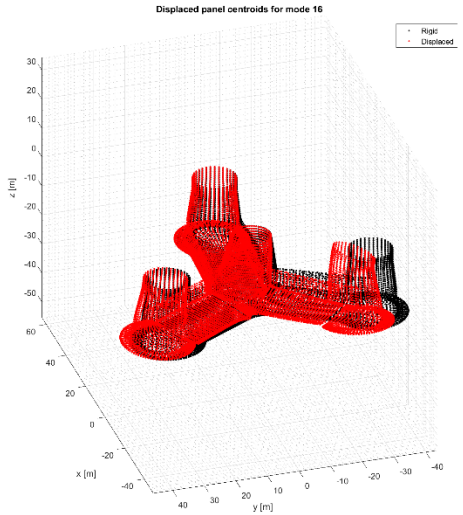
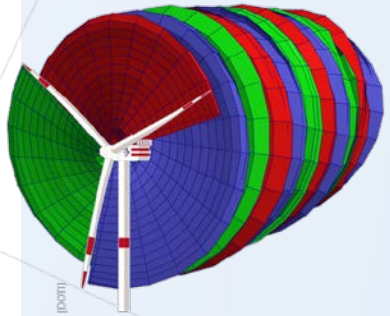
Wrap up





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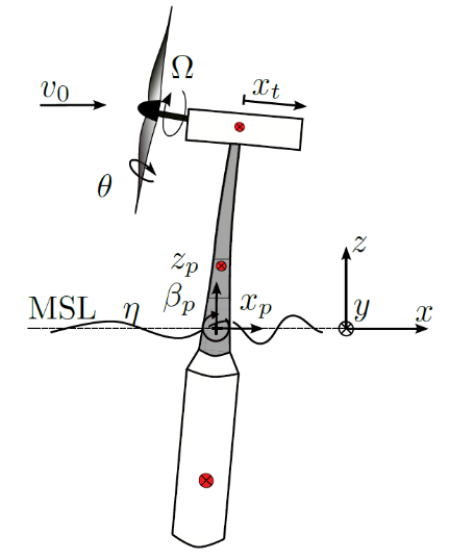

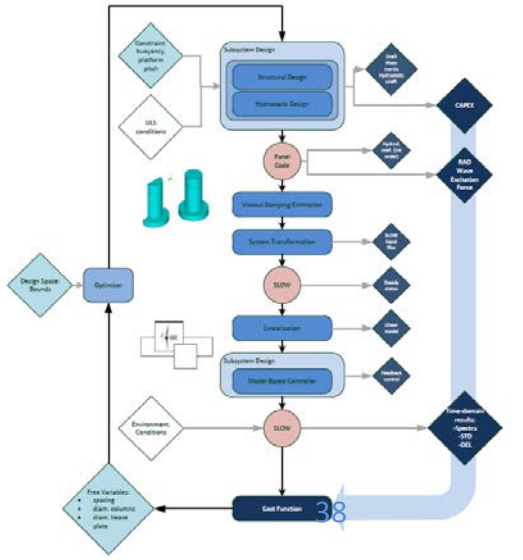

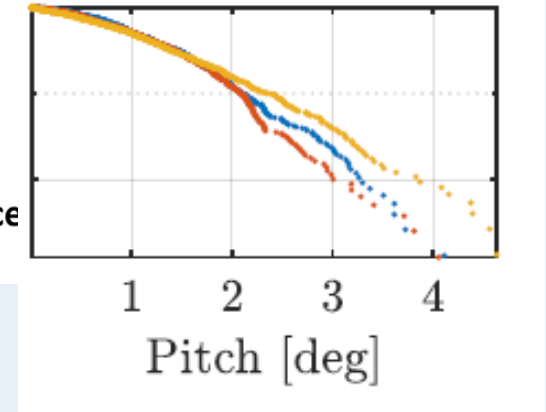

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THANK YOU!

www.lifes50plus.eu

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