Method and application for cost-effective monitoring of FOWTs

using a hybrid digital twin

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Ambition and challenges

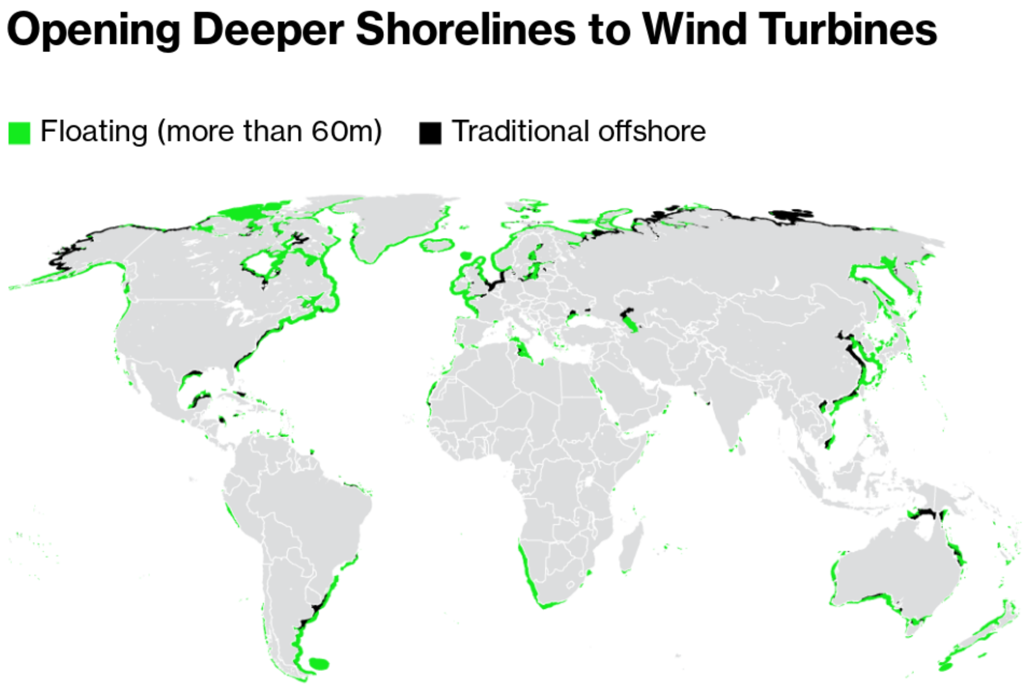
High ambitions for floating wind:

- World: Large deep water areas near load centers
- WindEurope: EU target for floating wind 2050 is 150GW
- Several demo/pilot sites operational
- Cost reduction -> large scale deployment

Challenges with mooring of FOWT:

- Significant contribution to system cost
- Extrapolation of O&G failure data indicates high failure rates
- Monitoring of mooring line loads difficult

but accurate platform motion -> 'virtual' line loads



Note: Suitable area winds exceed 7m/s and are situated within 55km and 200km from shoreline.
Data: British Oceanographic Data Centre, Global Wind Atlas

src: https://www.bloomberg.com/news/features/2020-06-05/floating-wind-farms-could-supply-the-world-s-electricity-by-2040

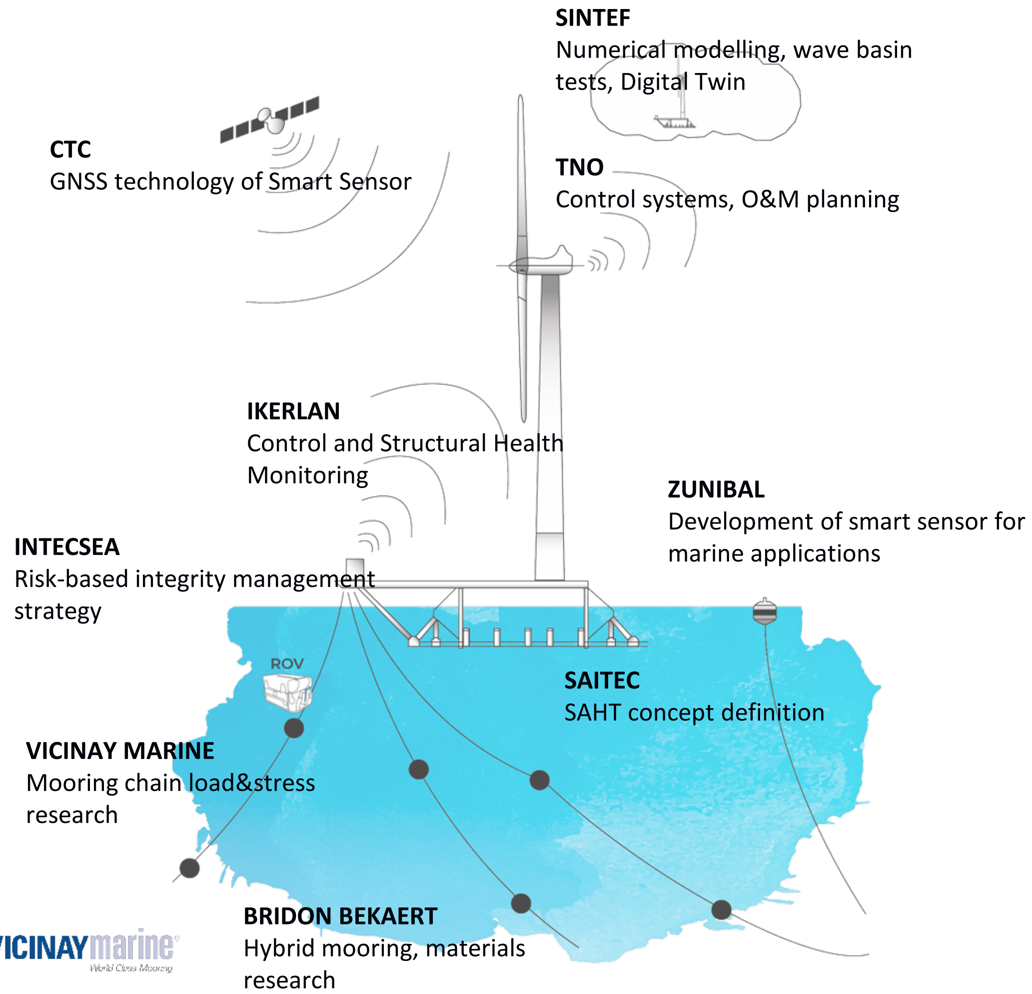
Introduction MooringSense

Funded project under grant agreement No 851703

The operators of future large floating wind farms will face several challenges:

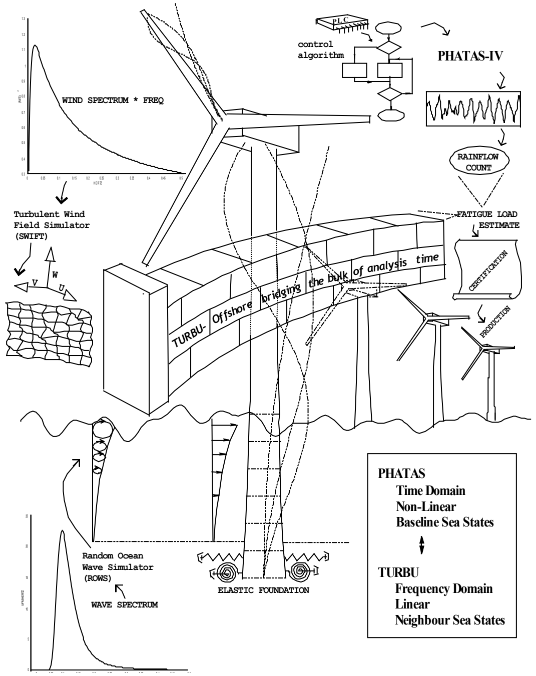
- How to efficiently monitor the large number of mooring systems?
- How to schedule maintenance to reduce OPEX and prevent failures?
- How to operate a farm of floating wind turbines?

H2020 MooringSense project (CTC, Saitec, Vicinay, Bridon, Zunibal, Intecsea, SINTEF, ikerlan, TNO) aimed at reducing operational costs and increasing efficiency through the development of an efficient risk-based integrity management strategy for mooring systems based on an affordable and reliable on-line monitoring technology.



Introduction TURBU

TURBU: fast, MatLAB based, aero-hydro-elastic wind turbine simulator

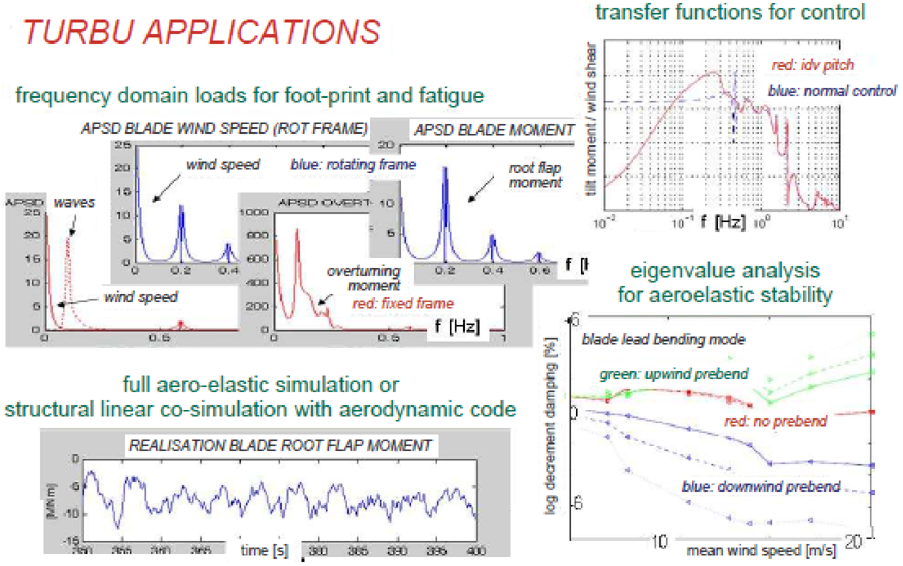


Features:

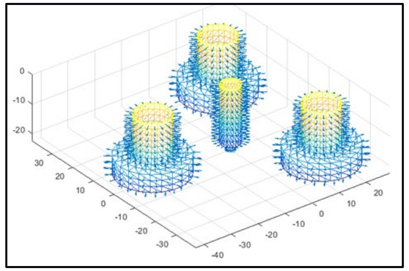
- Linear Time-Invariant (LTI) dynamic model (multi-body, Newton, Coleman)
- Configurable I/O (sensors & actuators)
- Wind and wave excitation
- Reduced order blade and tower models (Hurty, Craig-Bampton)
- Dynamic wake, unsteady aerodynamics

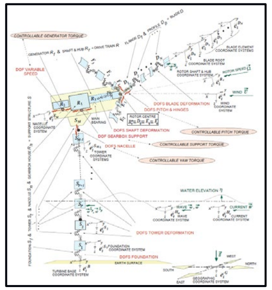
Use:

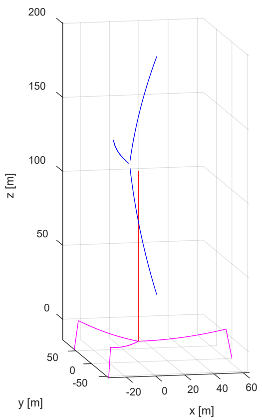
- Aeroelastic stability analysis (MOD)
- Load calculation (time&freq) for scoping predesign (LOAD)
- Control design (CTRL)

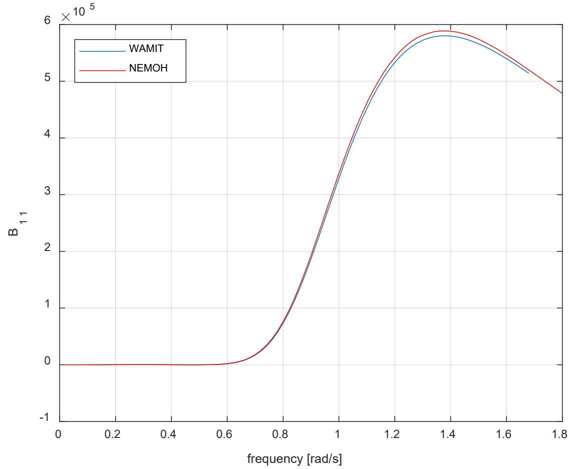


TURBU floating









hydrodynamic damping for first flexible mode

Two-stage approach for support structure model:

1. TURBU offshore floating (rigid body global motion):
   - (Non)linear time domain hydrodynamics from panel methods (e.g. NEMOH [1])
   - Linearization (as proposed by Perez&Fossen [2])
   - Linear mooring stiffness and possible additional damping
2. TURBU flexible support structure implementation:
   - Extended panel method for flexible platform modes
   - Assumption of Morison for initial inertia effect on modes
   - Beam approach for typical multi-legged platforms, covers most concepts (semi, TLP)
   - Other shapes could be included using externally derived Craig-Bampton modes/matrices

[1] A. Babarit, G. Delhommeau: Theoretical and numerical aspects of the open source BEM solver NEMOH. In Proc. of the 11th European Wave and Tidal Energy Conference, Nantes, France, 2015.

[2] T. Perez, T. Fossen; A Matlab Toolbox for Parametric Identification of Radiation-Force Models of Ships and Offshore Structures. In Modeling, Identification and Control, 30-1, 2009.

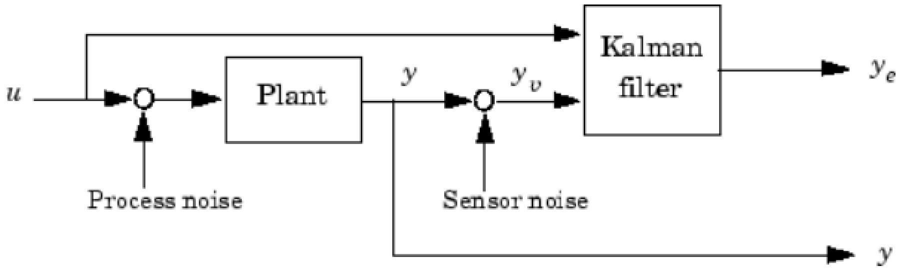
TURBU model as digital twin building block

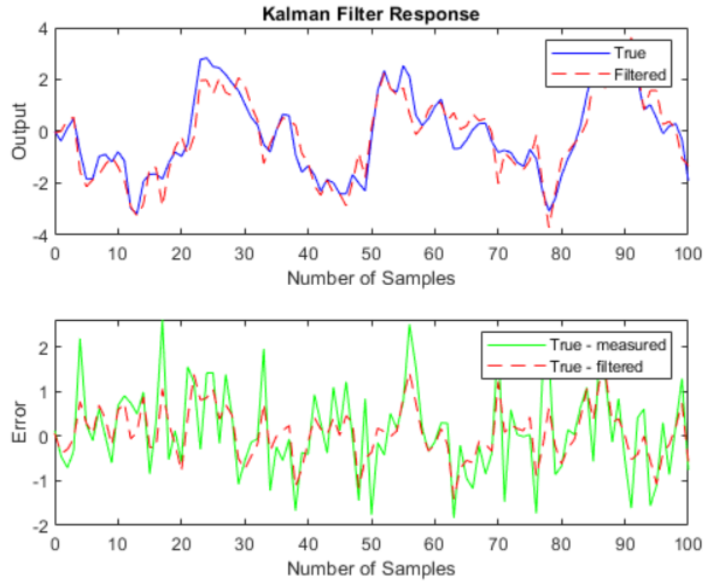
(augmented) Kalman Filter (aKF):

- Established method to improve measurement quality
- Model based approach, initially developed for linear systems
- Uses estimated covariance of process (Q) and measurement (R) noise to tune balance between measurements and states
- Extensions for nonlinear systems, high number of states etc.
- Unknown disturbance can be represented as augmented states

Use of aKF for this approach:

- Allows feeding measurements (rotor speed, loads, accelerometers) to improve estimates actual conditions
- Perfect fit with TURBU (LTI, fast)
- Wind excitation represented as augmented states using random walk model (integrated noise)





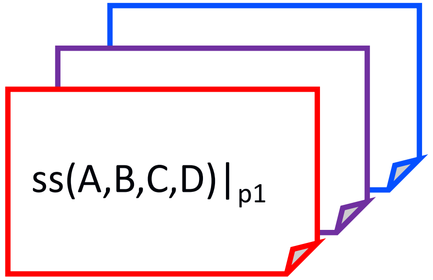
Kalman Filter based observer (src: MathWorks)

Stack of linear models to cover operating range

How to handle multiple operating points?

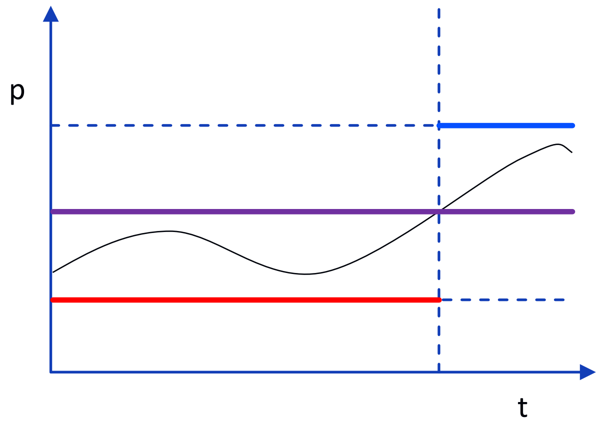
- Generate linear models for range of operating points
- Stack and stitch models, avoid jumps using initialization

-> Derive the ‘upward’ and ‘downward’ deviation of the state vector of each linear structural model when the conditions for the surrounding working points apply



Steps for time marching:

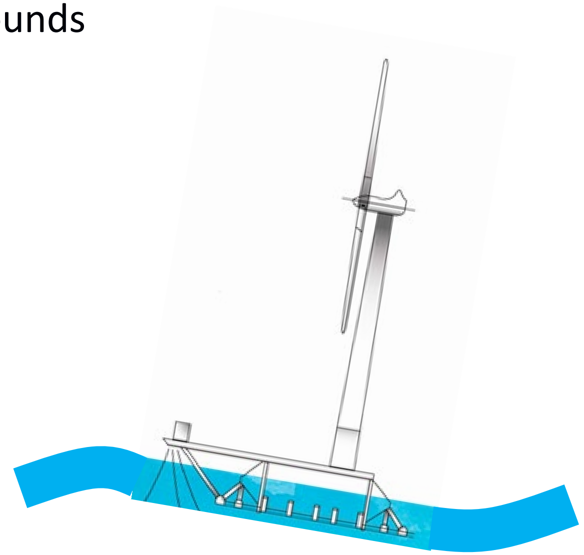
1. Select the working points down and up for the linear models that surround the actual working conditions
2. Initialize state vectors of linear models relative to surrounding working points in case of change of working of conditions
3. Update the state vector and compute the output vector of the actually surrounding models
4. Derive the output vector of the dynamic system as a weighted average of the output vectors of the linear models in the surrounding working points of the actual working conditions

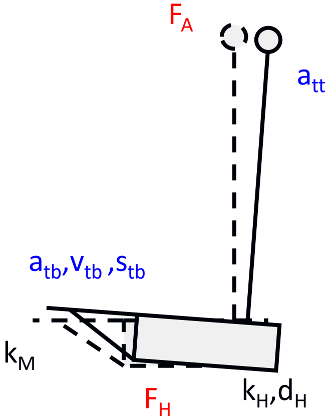


Online approach with unknown input

Shift to online method:

- Selection of operating point [V_w,Ω_r,θ_b,…] from available measurements/estimates; current approach:
  - Use of moving average of rotor equivalent estimated wind
  - Check on other quantities to be within expected bounds
- Joint estimation of input and state [3]
- Online KF implementation using subsequent
  1. Input update
  2. Measurement update
  3. Time update
- Measurement data pre&post processing





[3] E-M. Lourens, G. Lombaert, C. Papadimitriou and G. De Roeck, Joint estimation of states and input in linear structural dynamics. In proceedings of the ECCOMAS Conference, Corfu, Greece, 2011.

Offline test case with field measurements

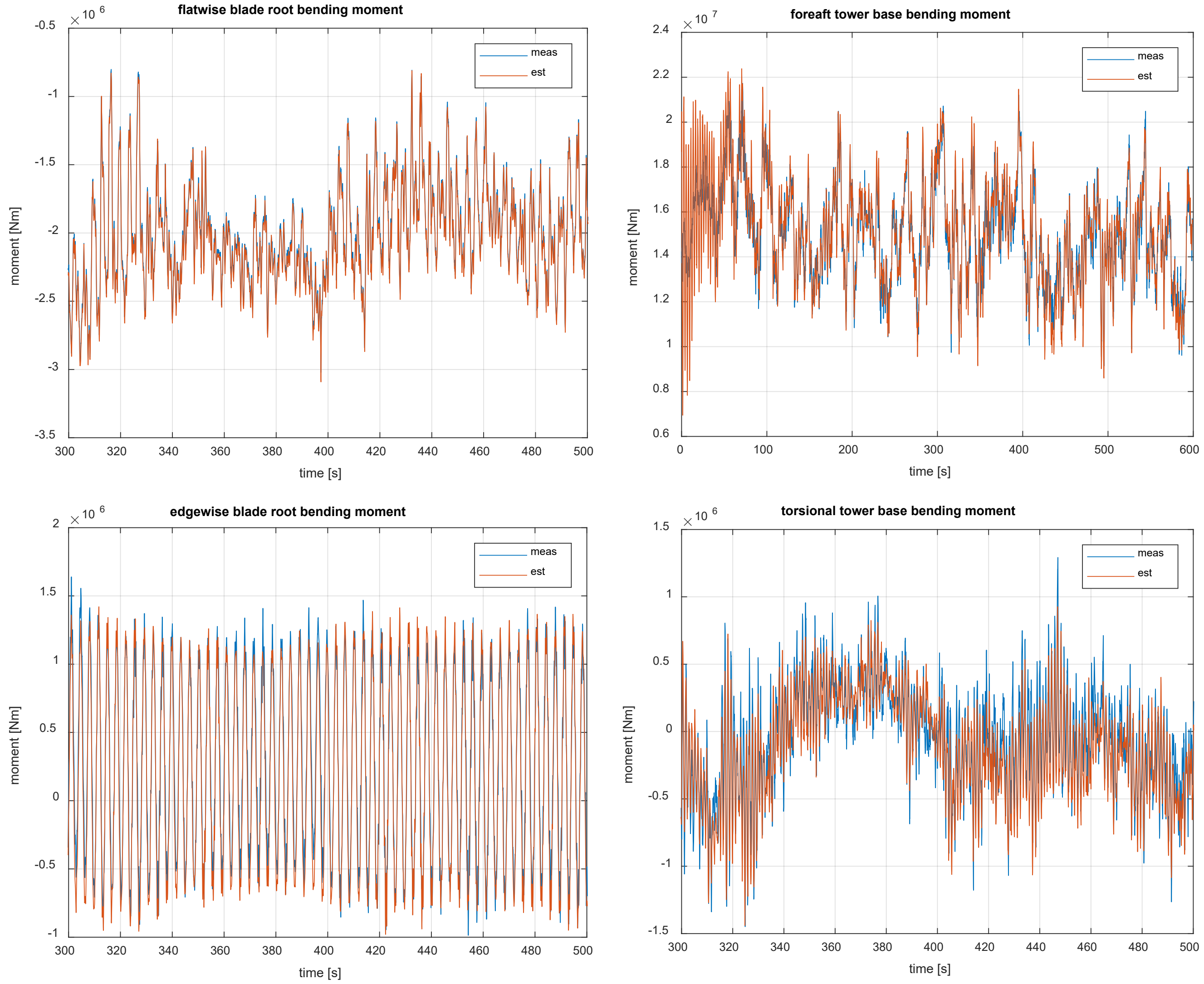
TURBU runs with aKF:

- Blade pitch angle as input
- Measured outputs rotor speed, blade flatwise bending moments

Above rated (wind speed 15.2m/s)

Observations on estimated outputs:

- Excellent flatwise blade root bending moments (sensor with high weight)
- Tower dynamics well captured (not inputs)
- Selection of sensors is key for observability

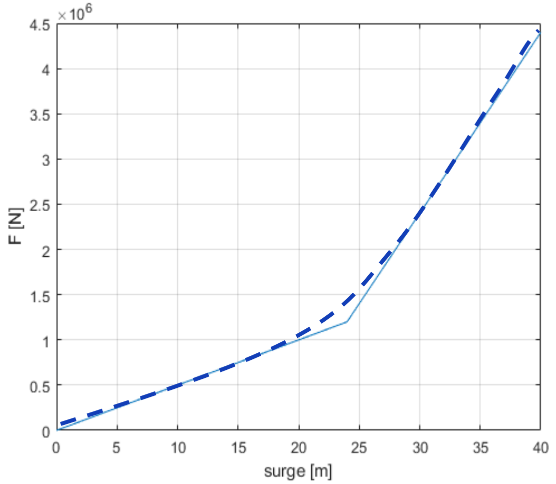


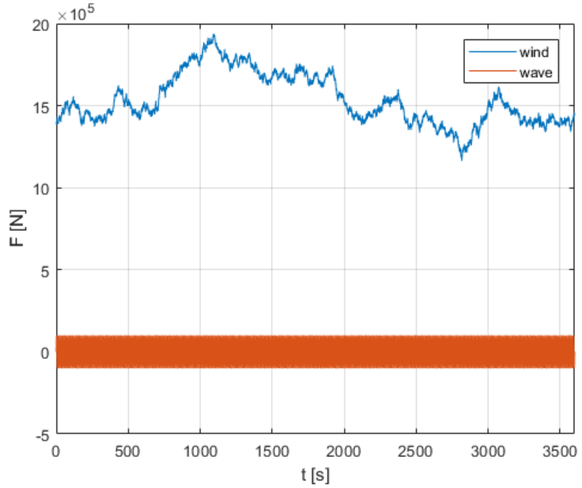
Simple test case for online floating application

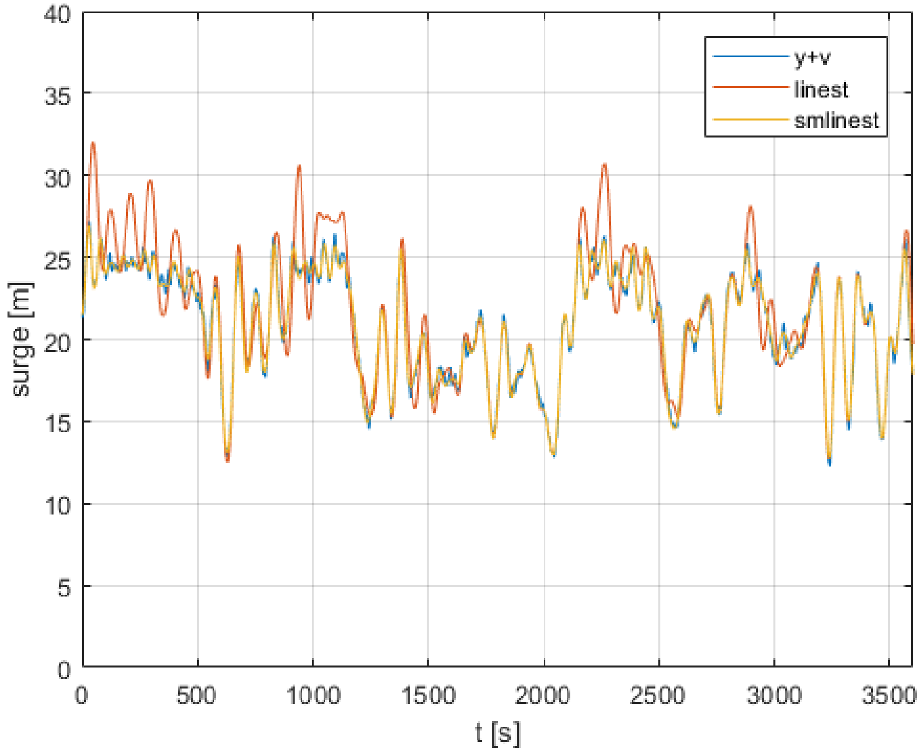
Example case to test proposed procedure:

- Simple mass-spring-damper system
- Wind and wave excitation
- Nonlinear (surge) stiffness

The stacked model estimator (smlinest) also captures the real motion in the higher stiffness range beyond 25m surge displacement.



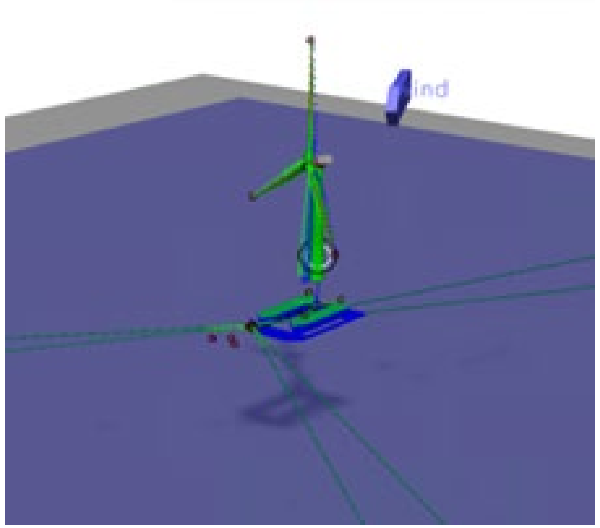




Online test on numerical simulations

Main observations:

- The proposed method is able to estimate main quantities of interest for operational cases, such as:
    - Inflow wind speed
    - Platform motions
    - Virtual load measurements at non-instrumented locations
- Tracking floater position and orientation results in very good estimates of mooring line loads; here the added value of the estimator depends on the availability and accuracy of sensors -> cost efficient!



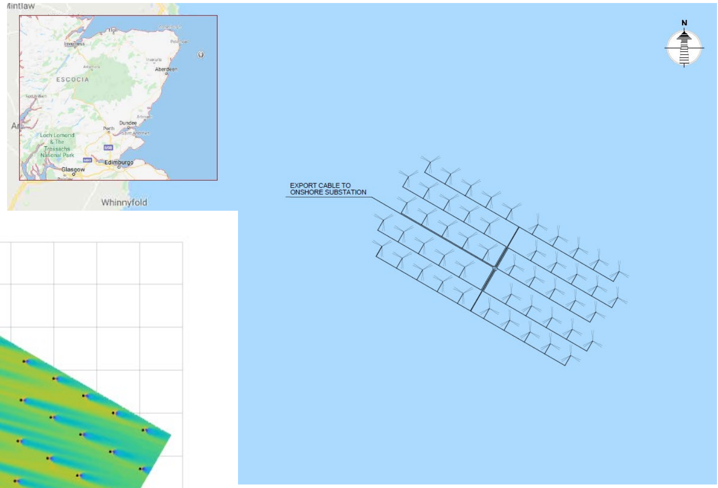
Online test on numerical simulations – farm level

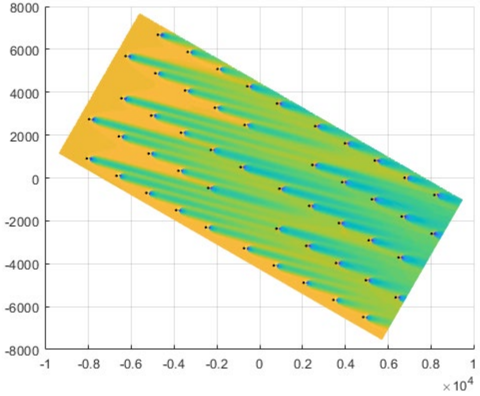
Reference system:

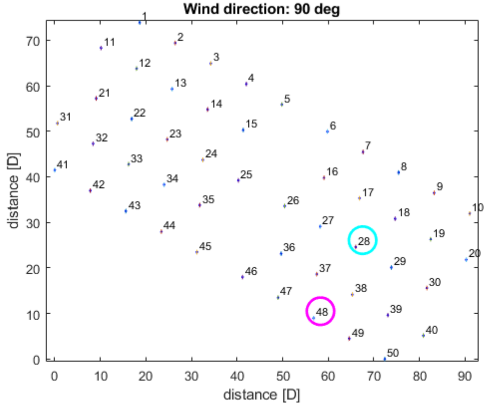
- FOWT: SATH floating support structure + DTU 10MW RWT
- FARM: 50 turbines at 9D spacing, Buchan Deep site

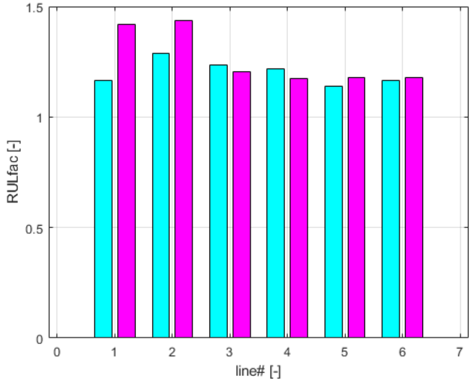
Main observations:

- Estimated mooring line loads follow calculated loads in wind farm setup
- The line load estimates allow for:
  - Modified operation: farm level power dispatching to reduce loading on heaviest loaded lines
  - Scheduling right-on-time line replacements / interchange









Outlook

Method looks promising, what are next steps?

- Test online approach in onshore field experiment (ongoing)
    - Implementation challenges (data handling, model reduction, etc.)
- Conclude on best sensor set to use for the selected system
- Extend analysis to larger set of operational cases and standstill
- Investigate different estimator methods:
    - Extended/Ensemble Kalman Filter
    - Particle filter [4]

TIADE at EWEF (src: J. Viscasillas)

[4] K. Merz, Particle filters for robust state observation and control of wind plants, Presented at the DeepWind2022 Conference, online, 2022.

Q&A

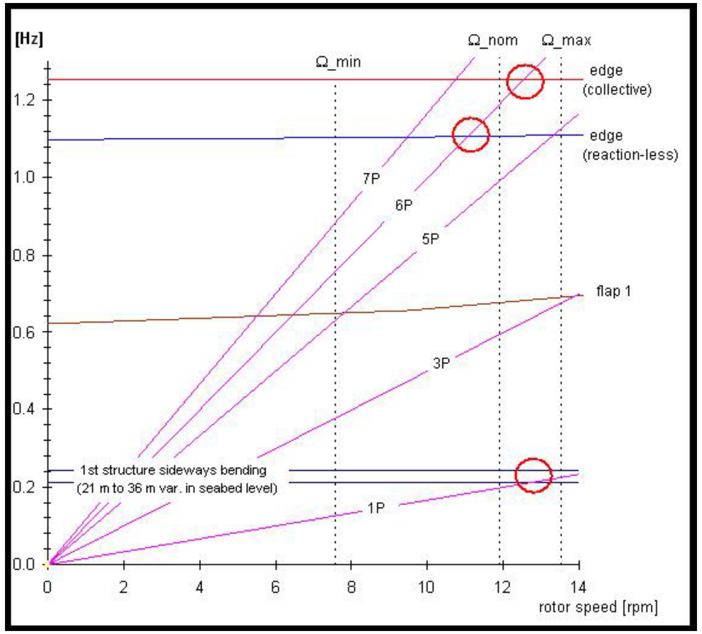
Acknowledgements:

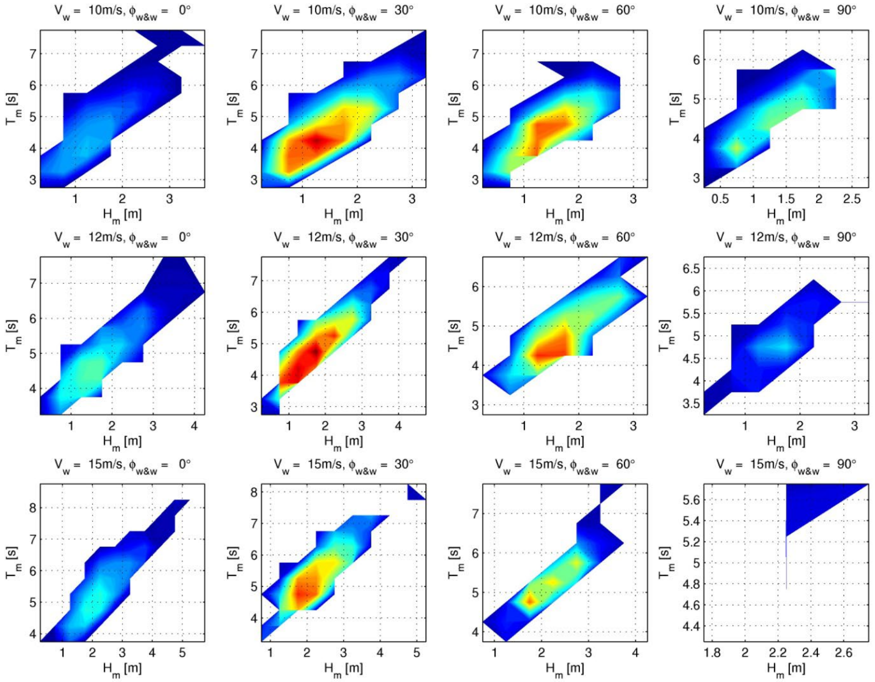
- Former colleagues Tim van Engelen and Koen Hermans
- MooringSense project team
- EU for supporting this work under GA#851703

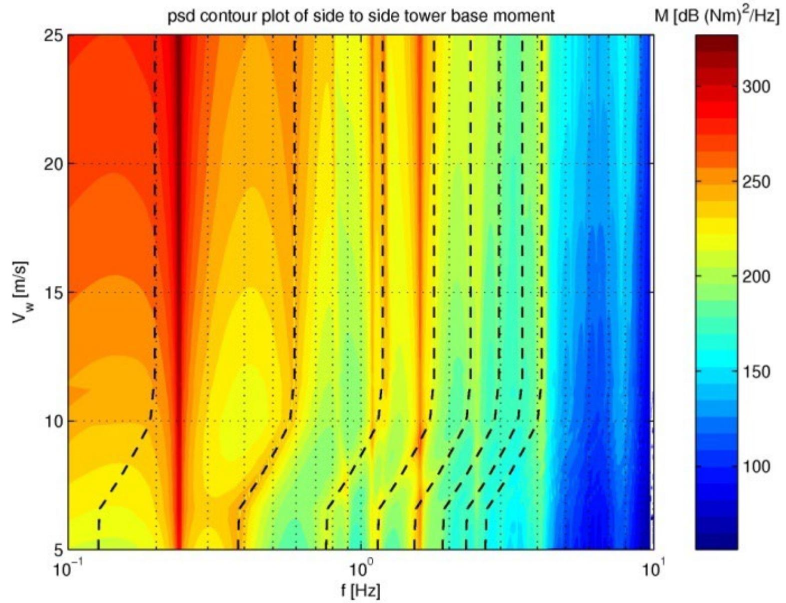
TURBU application

TURBU in We@Sea project [5]:

- Validation against Phatas load set
- Frequency analysis of offshore wind turbine
- Scoping load cases







[5] F.J. Savenije, J.M. Peeringa; Aero-elastic simulation of offshore wind turbines in the frequency domain, ECN-E--09-060