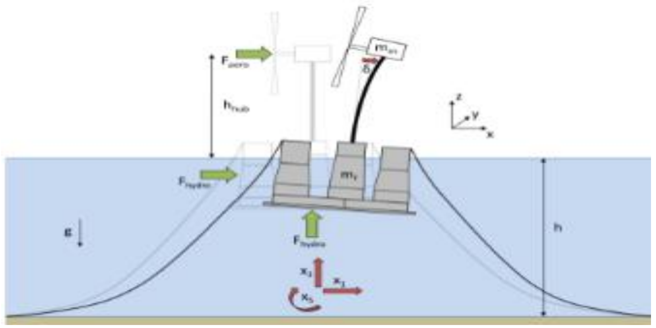
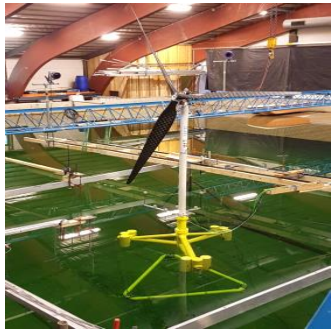
Innovation Fund Denmark

Accurate and validated design tools for floating wind turbine substructures

Recent results from the FloatStep project



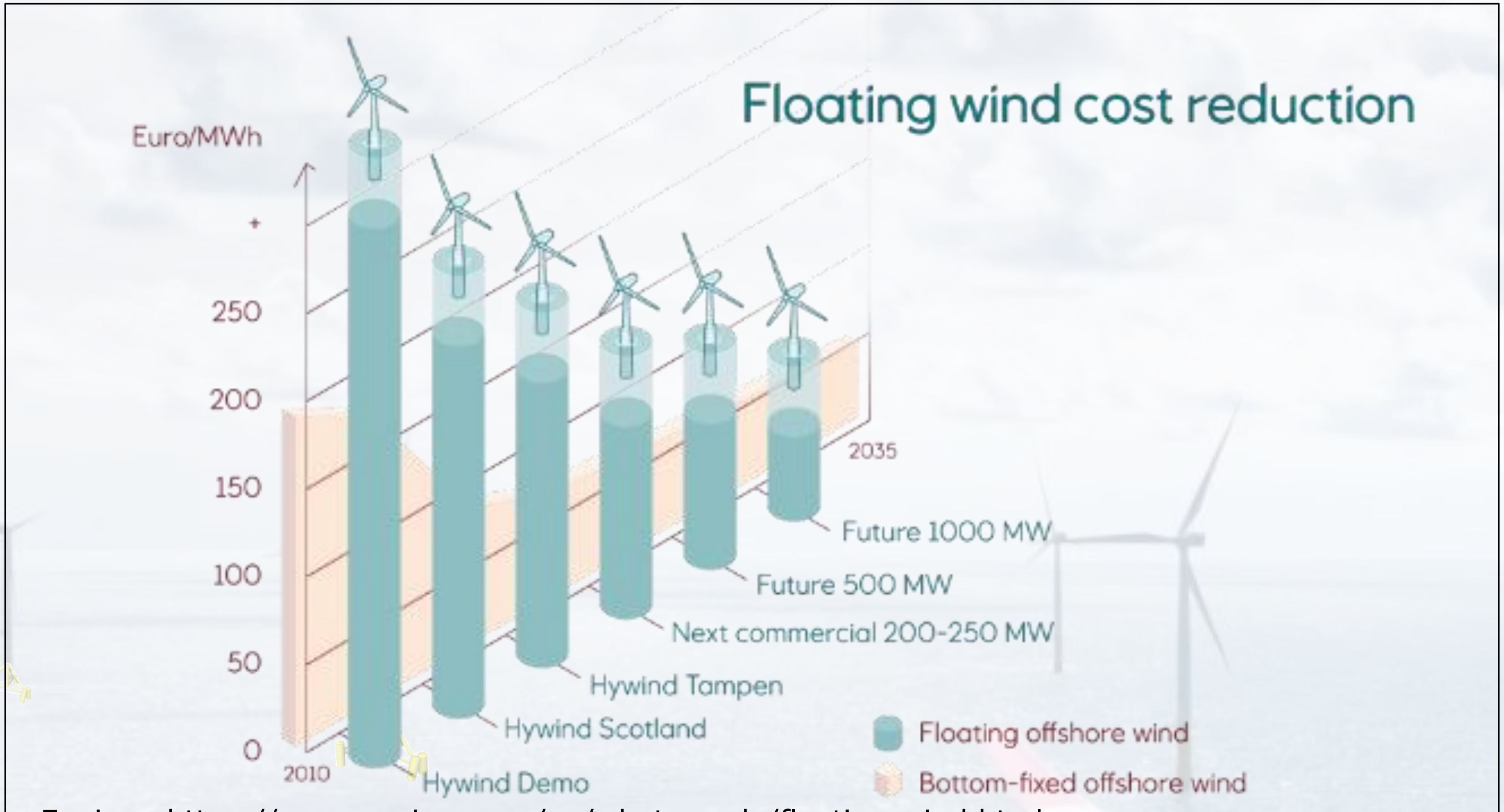


Henrik Bredmose[1], Antonio Pegalajar-Jurado[1], Christine L. Hansen[1], Nicoló Pollini[1], Kasper Laugesen[2], Bjarne Jensen[3], Michael Borg[4], Johan Rønby[5], Jana Orszaghova[6]

DTU 1
SIEMENS Gamesa RENEWABLE ENERGY 2
DHI 3
Stiesdal Offshore Technologies 4
STROMNING 5
THE UNIVERSITY OF WESTERN AUSTRALIA 6

Innovation Fund Denmark

Floating wind farms and the needed LCOE reduction



Equinor. https://www.equinor.com/en/what-we-do/floating-wind.html

The TetraSpar concept

Stiesdal Offshore Technologies

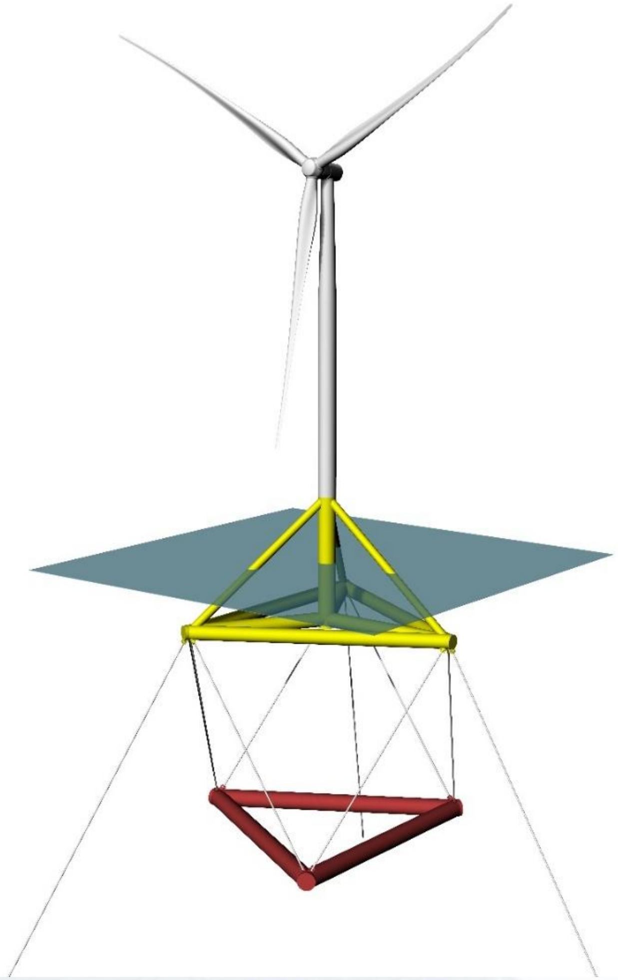
Innovation Fund Denmark

Mindset

- Conventional thinking
  - We have designed this structure – now, how do we build it?
- TetraSpar thinking
  - We need to manufacture this way – now, how do we design it?

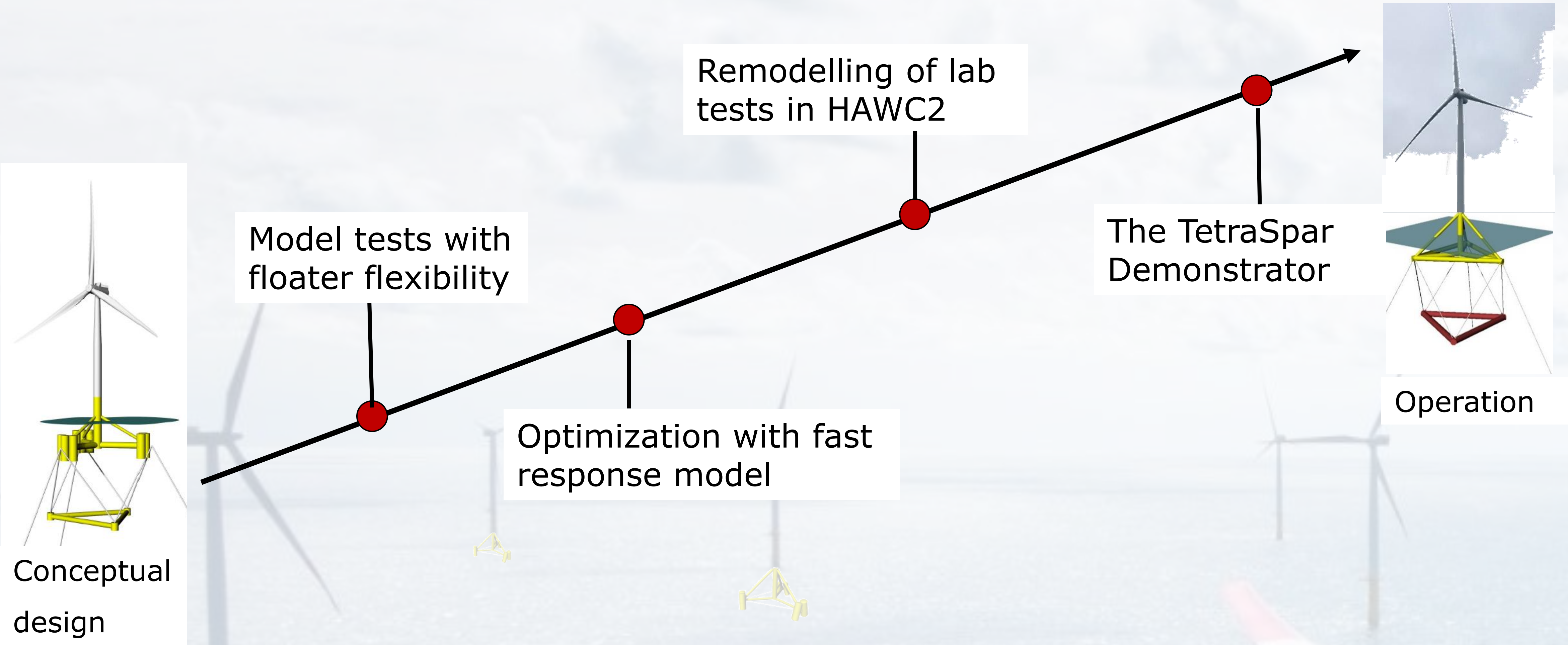
Concept

- Modular – all components factory-made, transported by road
- Components assembled at quayside with bolts (not exposed to sea water)
- Turbine mounted in harbor and towed to site, no installation vessels
- Weight 1000-1500 t for 6 MW turbine

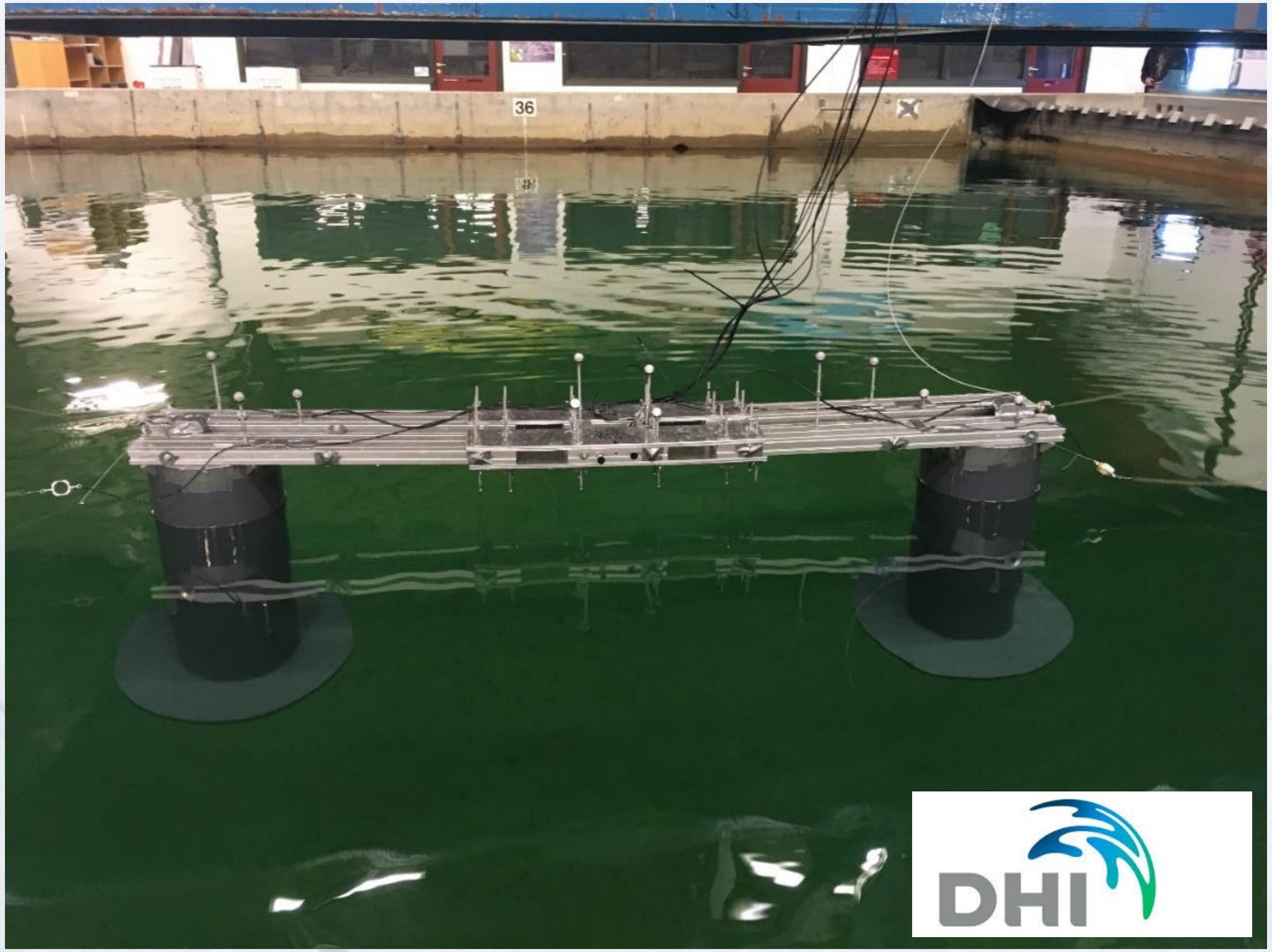


Innovation Fund Denmark

FloatStep: Validated and efficient design tools



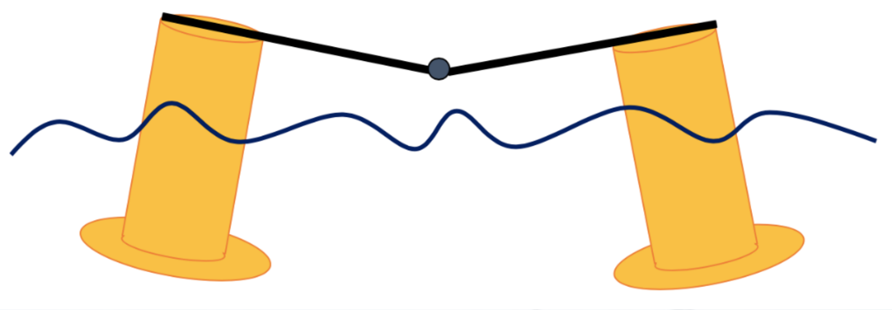
Model tests with flexible floater



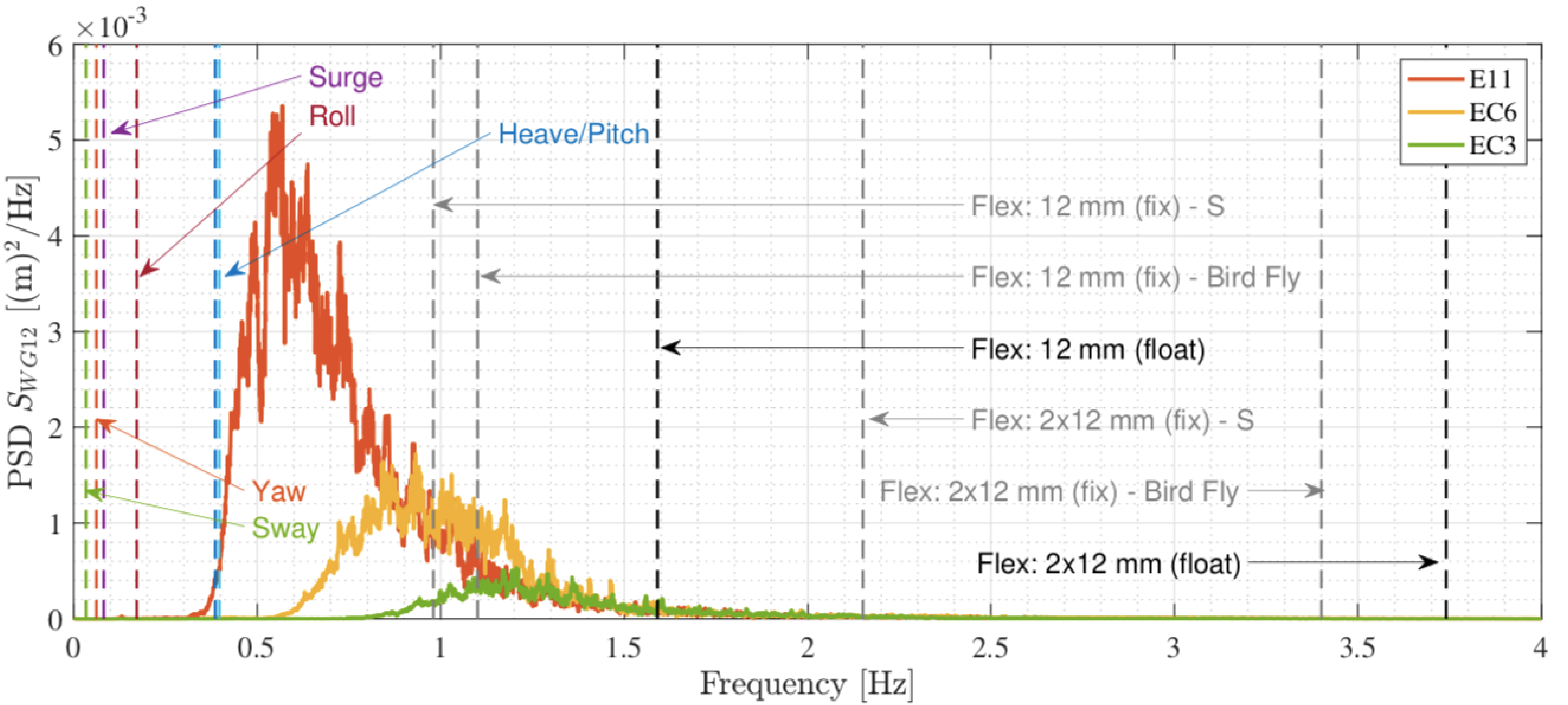
2-cylinder with heave plate structure

Flexible beam

Adjustable flexibility: (12 or 24 mm thickness)

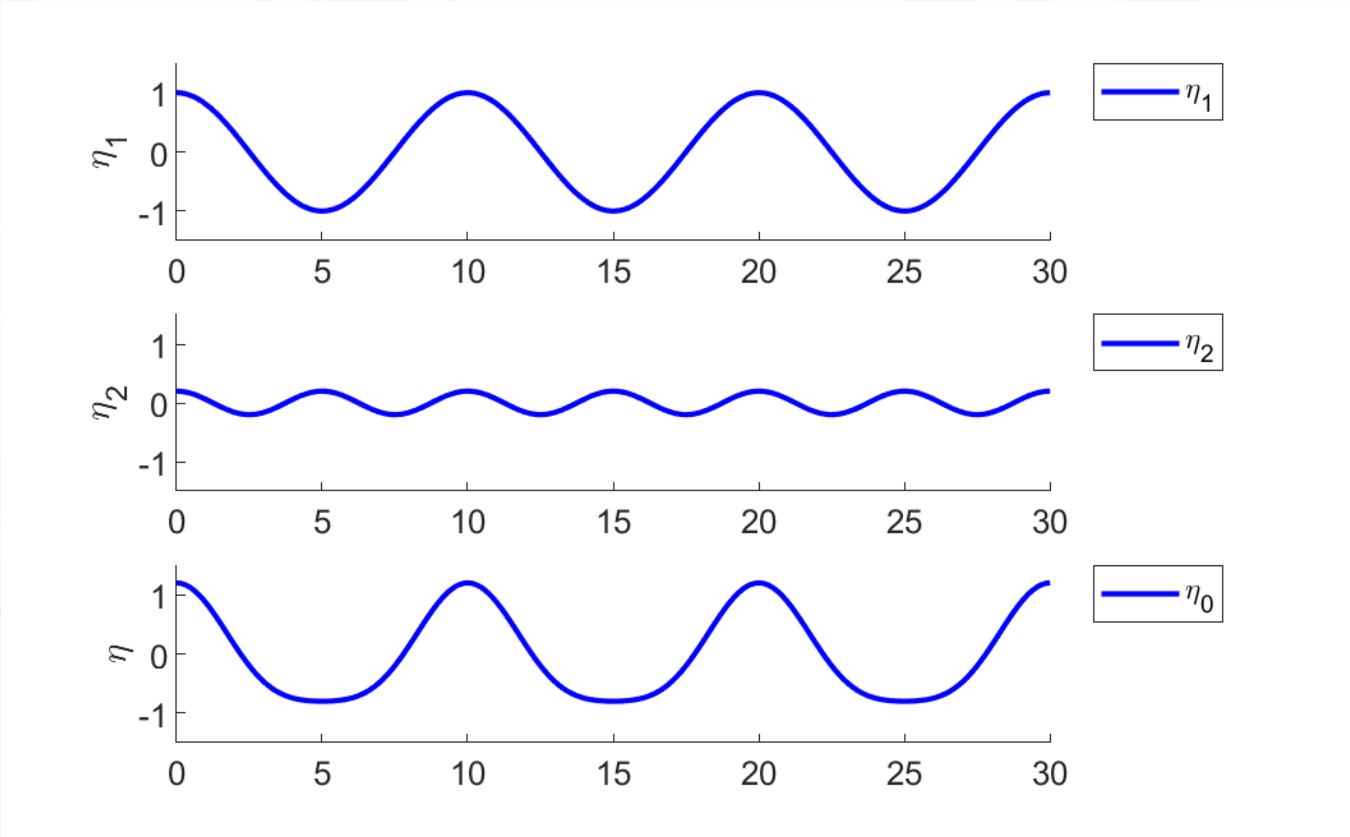


Natural frequencies and wave climates



Methodology – Harmonic separation

Walker, Taylor & Eatock Taylor (2004)



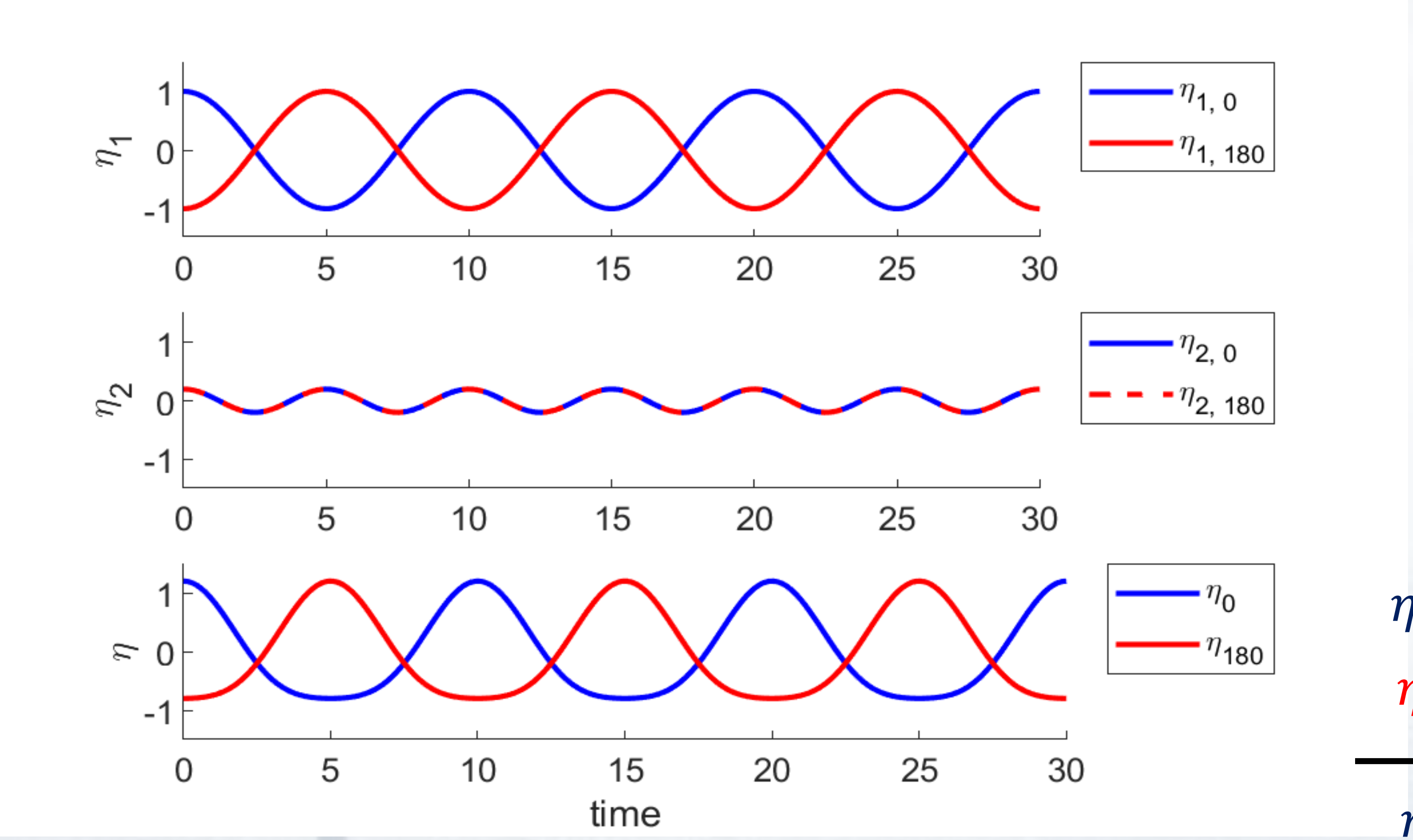
$$\eta_1 = a\cos\omega t$$

$$\eta_2 = c_{11}a^2\cos 2\omega t$$

$$\eta_0 = \eta_1 + \eta_2$$

Methodology – Harmonic decomposition

Walker, Taylor & Eatock Taylor (2004)



$$\eta_1 = a \cos \omega t$$

$$\eta_2 = c_{11} a^2 \cos 2\omega t$$

$$\eta_0 = \eta_1 + \eta_2$$

$$\eta_{180} = -\eta_1 + \eta_2$$

$$\eta_1 = (\eta_0 - \eta_{180})/2$$

$$\eta_2 = (\eta_0 + \eta_{180})/2$$

Four-phase harmonic separation

- Fitzgerald et al (2014; Method)
- Ghadirian et al (2019; Numerical for monopile loads)
- Orzaghova et al (2021; Experimental, floating, FloatStep)

$$Q^{(1)} = \frac{Q_0 - Q_{90}^H - Q_{180} + Q_{270}^H}{4} = Aq_{11}\cos\phi + A^2 f_D \cos\phi + A^3 q_{31}\cos\phi + O(A^5)$$

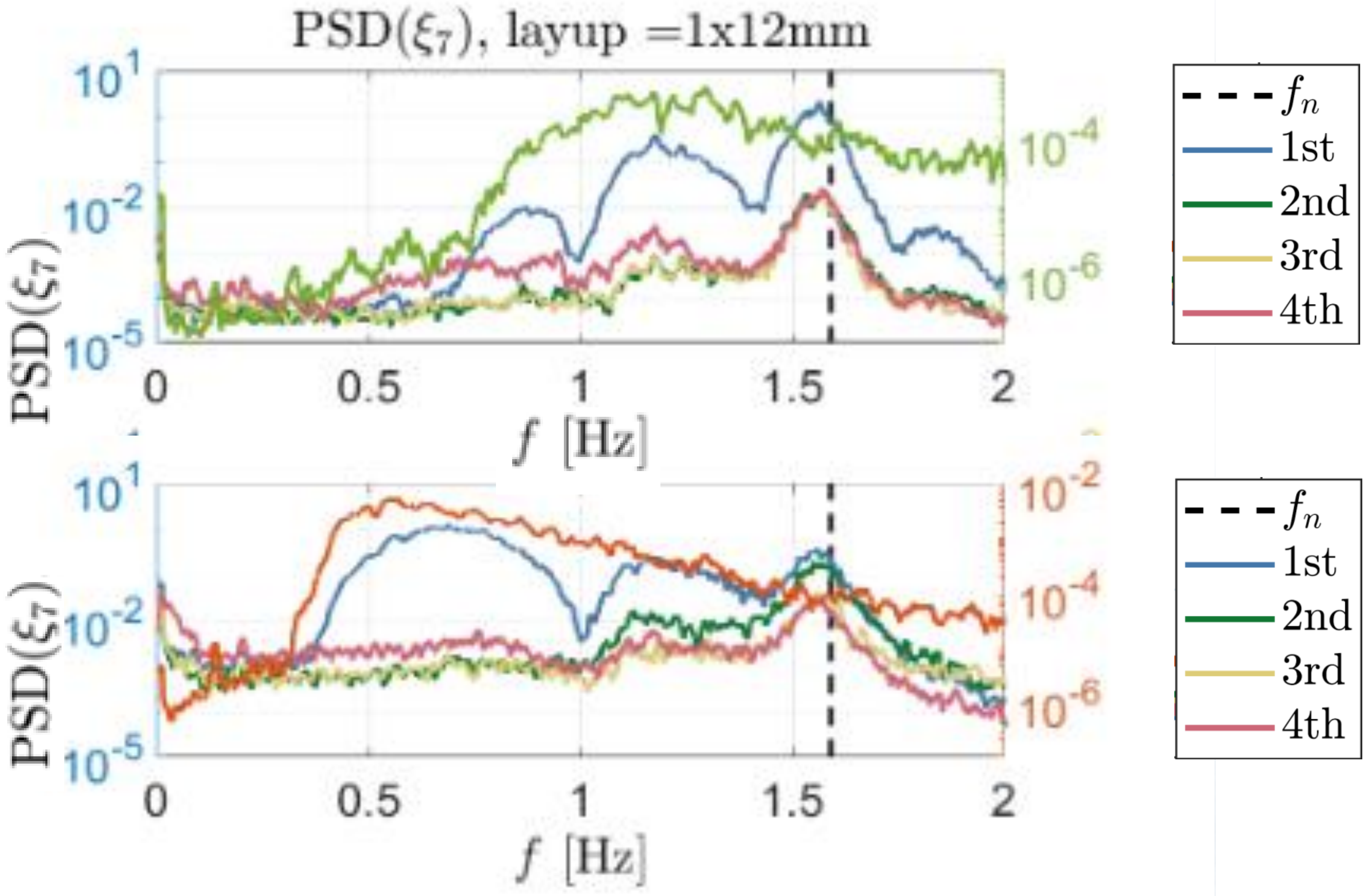
$$Q^{(2)} = \frac{Q_0 - Q_{90} + Q_{180} - Q_{270}}{4} = A^2 q_{22}\cos 2\phi + A^4 q_{42}\cos 2\phi + O(A^6)$$

$$Q^{(3)} = \frac{Q_0 + Q_{90}^H - Q_{180} - Q_{270}^H}{4} = A^2 f_D \cos 3\phi + A^3 q_{33}\cos 3\phi + O(A^5)$$

$$Q^{(4)} = \frac{Q_0 + Q_{90} + Q_{180} + Q_{270}}{4} = A^2 q_{20} + A^4 q_{40} + A^4 q_{44}\cos 4\phi + O(A^6)$$

Allows harmonic content to be separated into 1st, 2nd, 3rd and 4th harmonic

Flexible mode - Analysis by harmonic separation



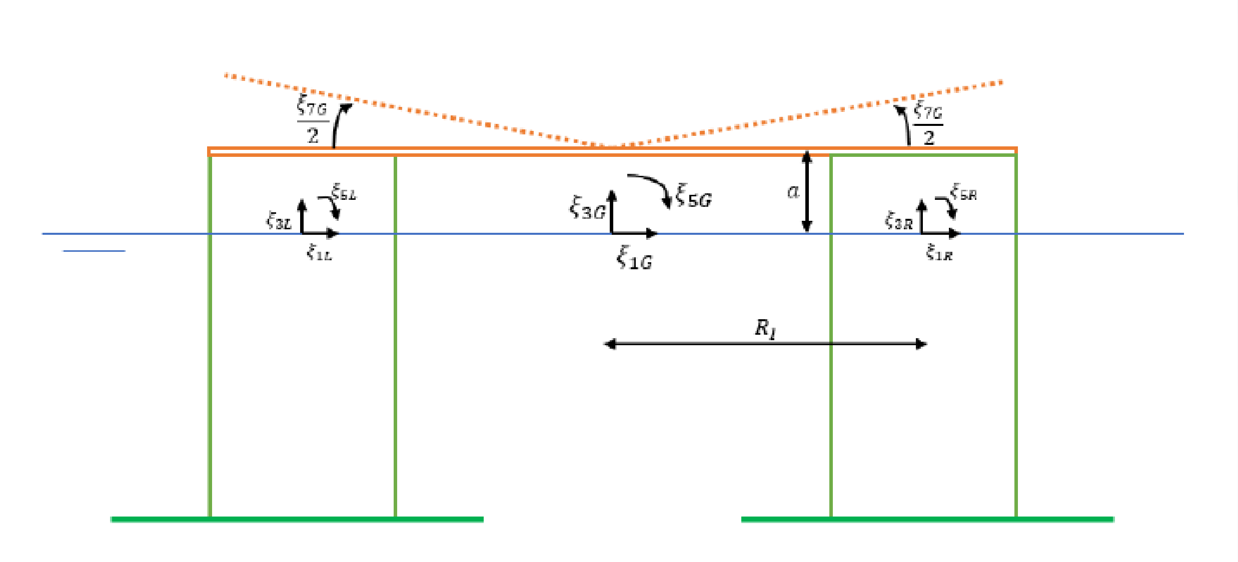
Weak sea state (top green line)

Flexible mode at 1.6 Hz driven linearly

Storm sea state (top red line)

Flexible mode at 1.6 Hz strong 2nd-order contribution

Reproduction in Morison based model



Two stiff beams with torsional spring

Second-order wave forcing accelerated O(N log N)

Rainey force model (inertia loads)

Drag force

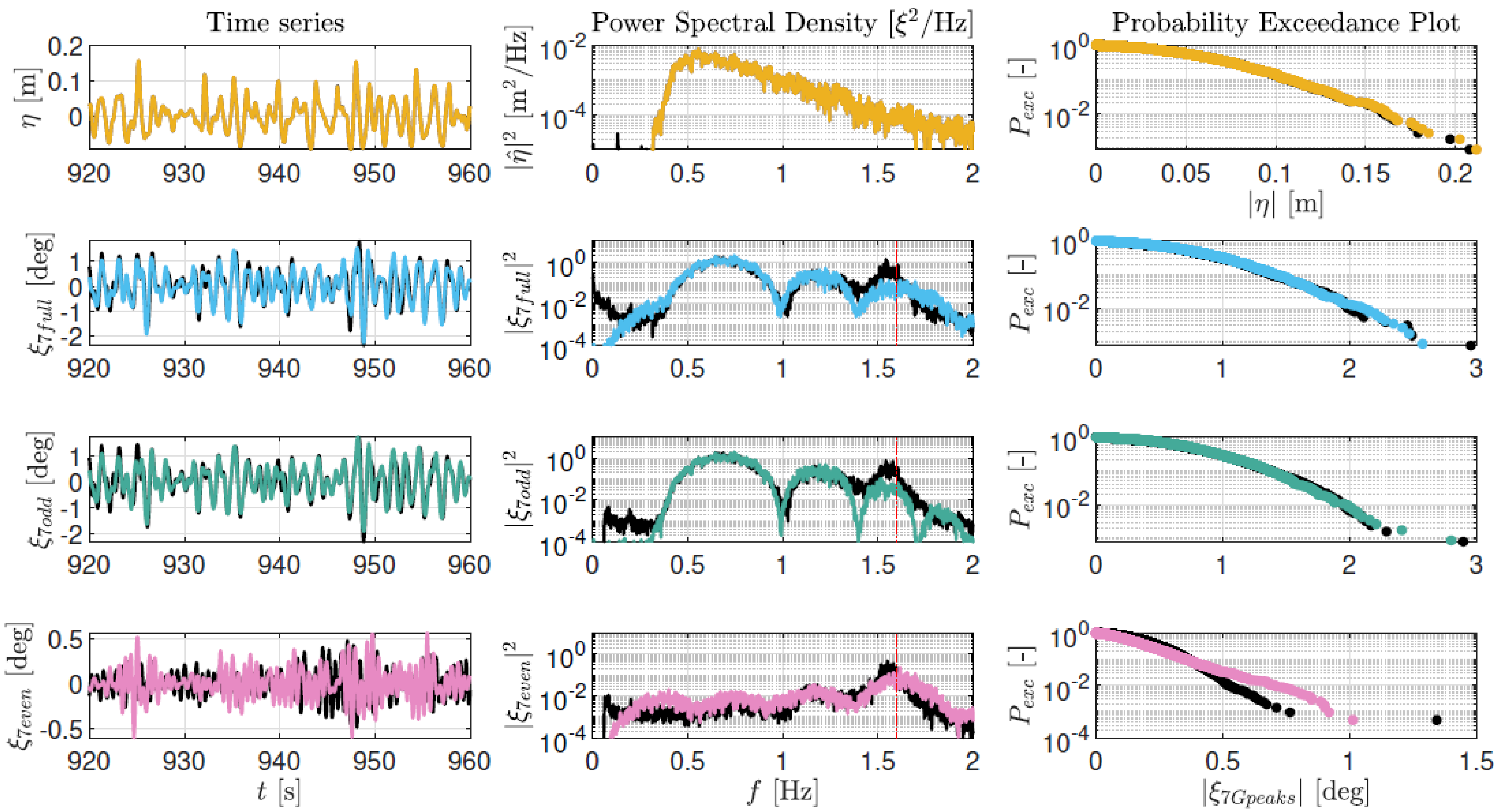
Calibrated modal damping

Further info:

- Hansen et al (2022 – in preparation)
- MSc thesis Maude Vincent (2020)
- MSc thesis Christine Lynggaard Hansen (2021)
- Bredmose & Pegalajar-Jurado (2021)

Innovation Fund Denmark

Reproduction: Storm sea state



Measurements in black

Hansen et al (2022 – in preparation)

Free surface elevation

Total flexible motion

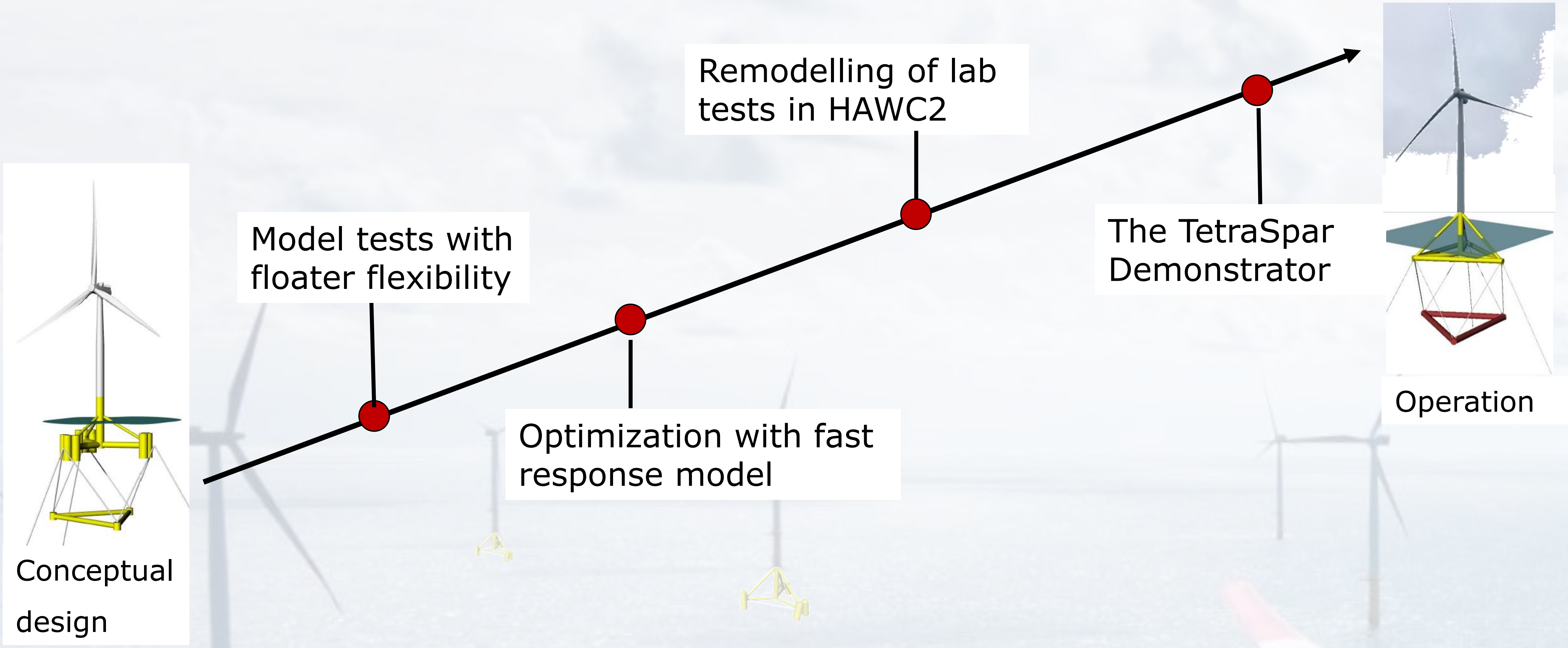
Linear + drag

Second-harmonic (second-order inviscid)

Successful reproduction of flexible motion to second order.

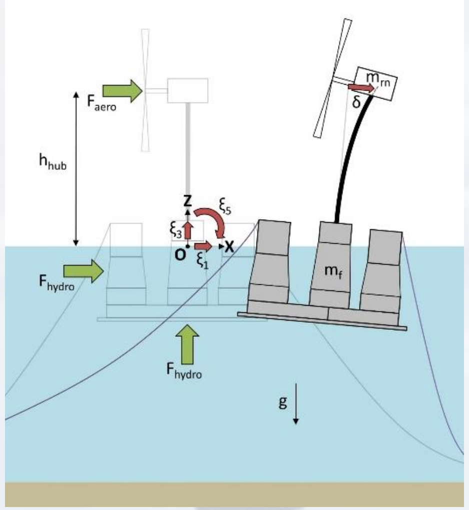
Innovation Fund Denmark

Validated and efficient design tools



15 MW TetraSpar type design by QuLAF and optimization

The QuLAF model



Precompute rotor loads and aero damping

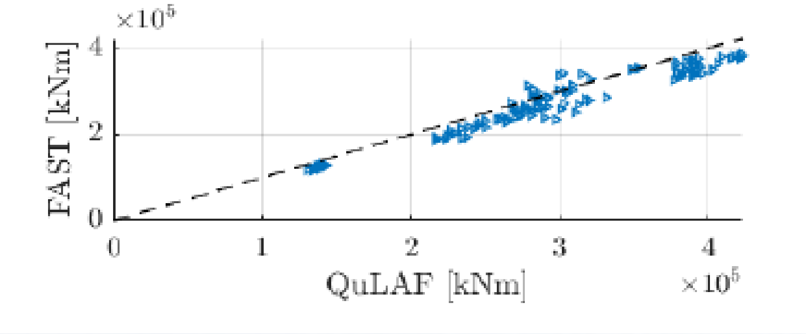
3 floater DOFs
1 tower DOF

WAMIT data for hydro
Linearized mooring

2000 x real time

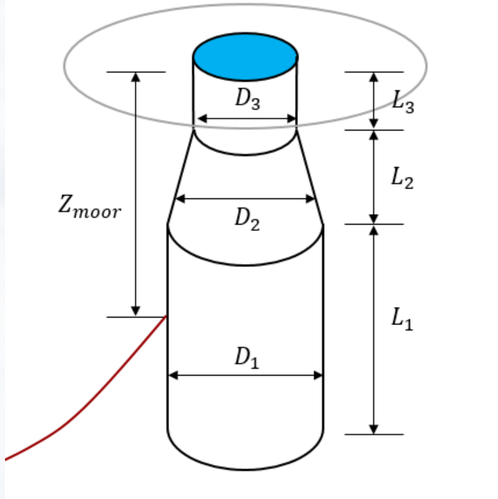
Pegalajar-Jurado et al (2018)

Validation study
Tower bottom moment



Madsen et al (2019)

Spar designs in FloatStep:



Dou et al (2020)
Pollini et al (2021)

See also Hegseth et al (2020)

Innovation Fund Denmark

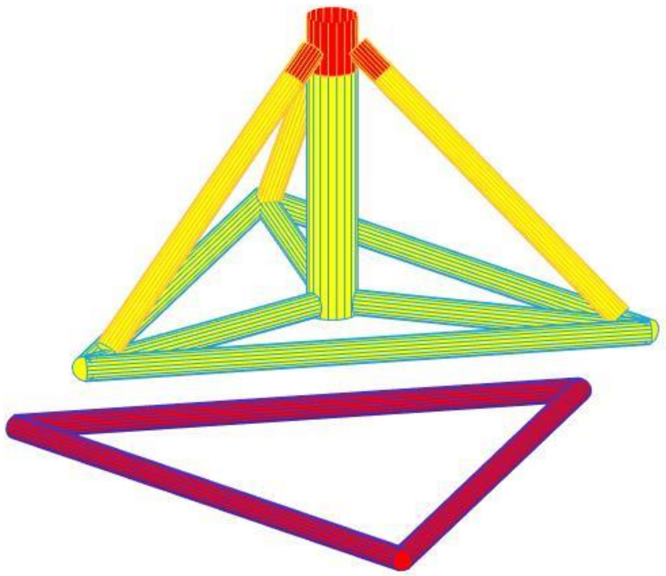
The IEA WIND 15-MW offshore reference wind turbine

Gaertner, Evan, Jennifer Rinker, Latha Sethuraman, Frederik Zahle, Benjamin Anderson, Garrett Barter, Nikhar Abbas, Fanzhong Meng, Pietro Bortolotti, Witold Skrzypinski, George Scott, Roland Feil, Henrik Bredmose, Katherine Dykes, Matt Shields, Christopher Allen, and Anthony Viselli. 2020. *Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75698.https://www.nrel.gov/docs/fy20osti/75698.pdf

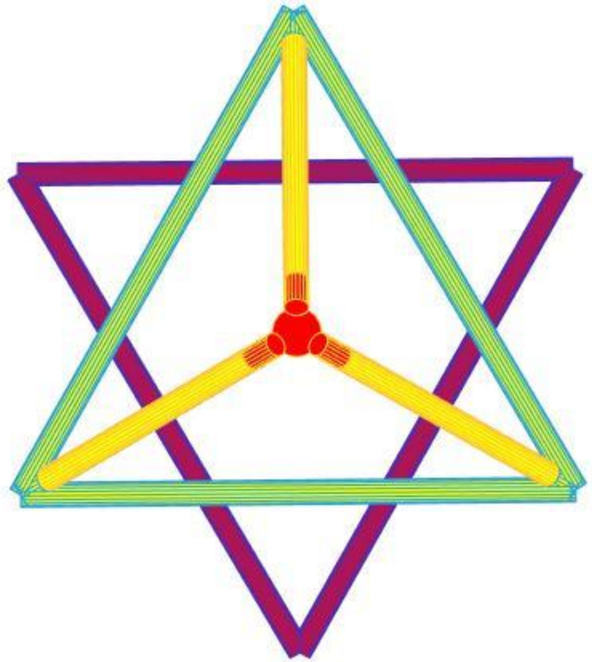
Made by NREL and DTU
Publically available as FAST and HAWC2 models at https://github.com/IEAWindTask37/IEA-15-240-RWT

Innovation Fund Denmark

Extension to optimization with motion 6+1 DOFs



Currently:
6 DOFs of the floater
1 DOFs of the tower



x1: L central column
x2: D central column
x3: L pontoon
x4: D pontoon
x5: D brace
x6: D horizontal brace
x7: Depth of keel
x8: Depth fairlead
x9: Anchor radius
x10: Mooring line length

Nicoló Pollini ++

Governing equations

- Design variables ($\mathbf{v}$): geometric properties of the floater and the mooring system.
- The equations of motion for a floating wind turbine in QuLAF are:

$$\left(-\omega^2\left(\mathbf{M}(\mathbf{v})+\mathbf{A}(\mathbf{v})\right)+i\,\omega\mathbf{B}(\mathbf{v})+\mathbf{C}(\mathbf{v})\right)\widehat{\boldsymbol{\xi}}_j(\omega)=\widehat{\mathbf{F}}_j^{\mathrm{h}}(\mathbf{v},\omega)+\widehat{\mathbf{F}}_j^{\mathrm{a}}(\omega)$$

- $\mathbf{M}$ structural mass; $\mathbf{A}$ added mass; $\mathbf{B}$ damping; $\mathbf{C}$ restoring matrix (hydrostatic and mooring); $\mathbf{F}^{\mathrm{h}}$ hydrodynamic loads (Morison’s equation); $\mathbf{F}^{\mathrm{a}}$ precomputed aerodynamic loads.
- The optimization problem includes limits on eigenvalues from the eigenvalue problems

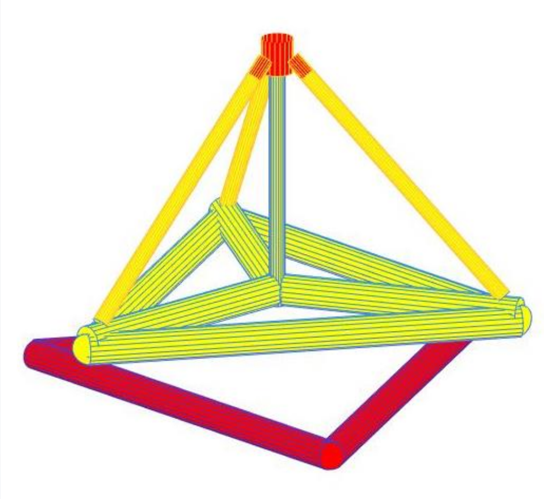
$$(\mathbf{C}(\mathbf{v})-\lambda_i(\mathbf{M}(\mathbf{v})+\mathbf{A}(\mathbf{v})))\boldsymbol{\phi}_i=\mathbf{0}$$

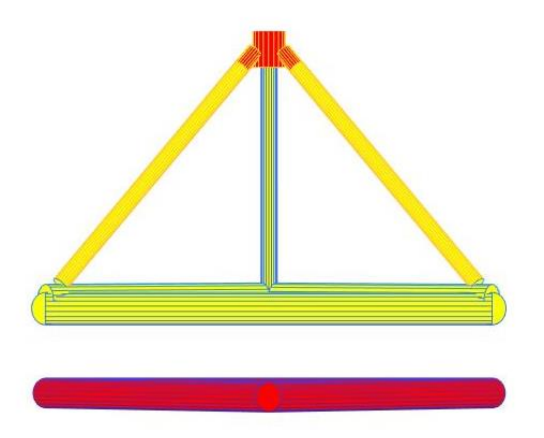
- and limits on the maximum static responses

$$\mathbf{C}(\mathbf{v})\mathbf{u}=\mathbf{f}^s$$

Dou et al (2020)
Pollini et al (2021)

Initial results – no transient dynamic constraints



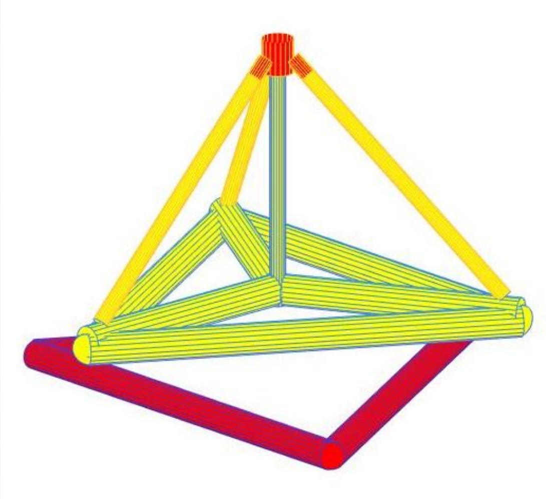


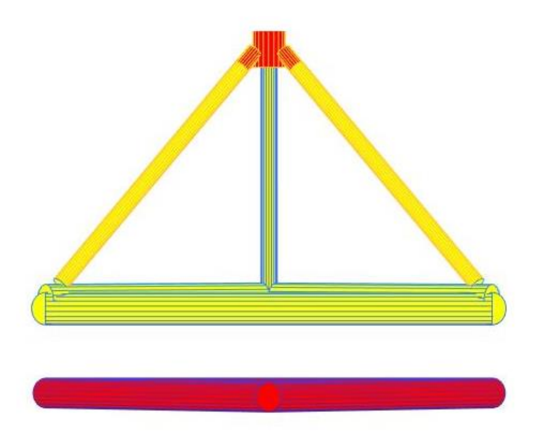
Initial height of central column: 50.000 meter
Initial diameter of central column: 10.000 meter
Initial length of pontoon: 65.000 meter
Initial diameter of pontoon: 5.000 meter
Initial diameter of brace: 5.000 meter
Initial diameter of horizontal brace: 5.000 meter
Initial depth of keel from msl: -80.000 meter
Initial depth of fairlead: -10.000 meter
Initial anchor radius: 650.000 meter
Initial mooring line length: 750.000 meter
cost: 21.5579

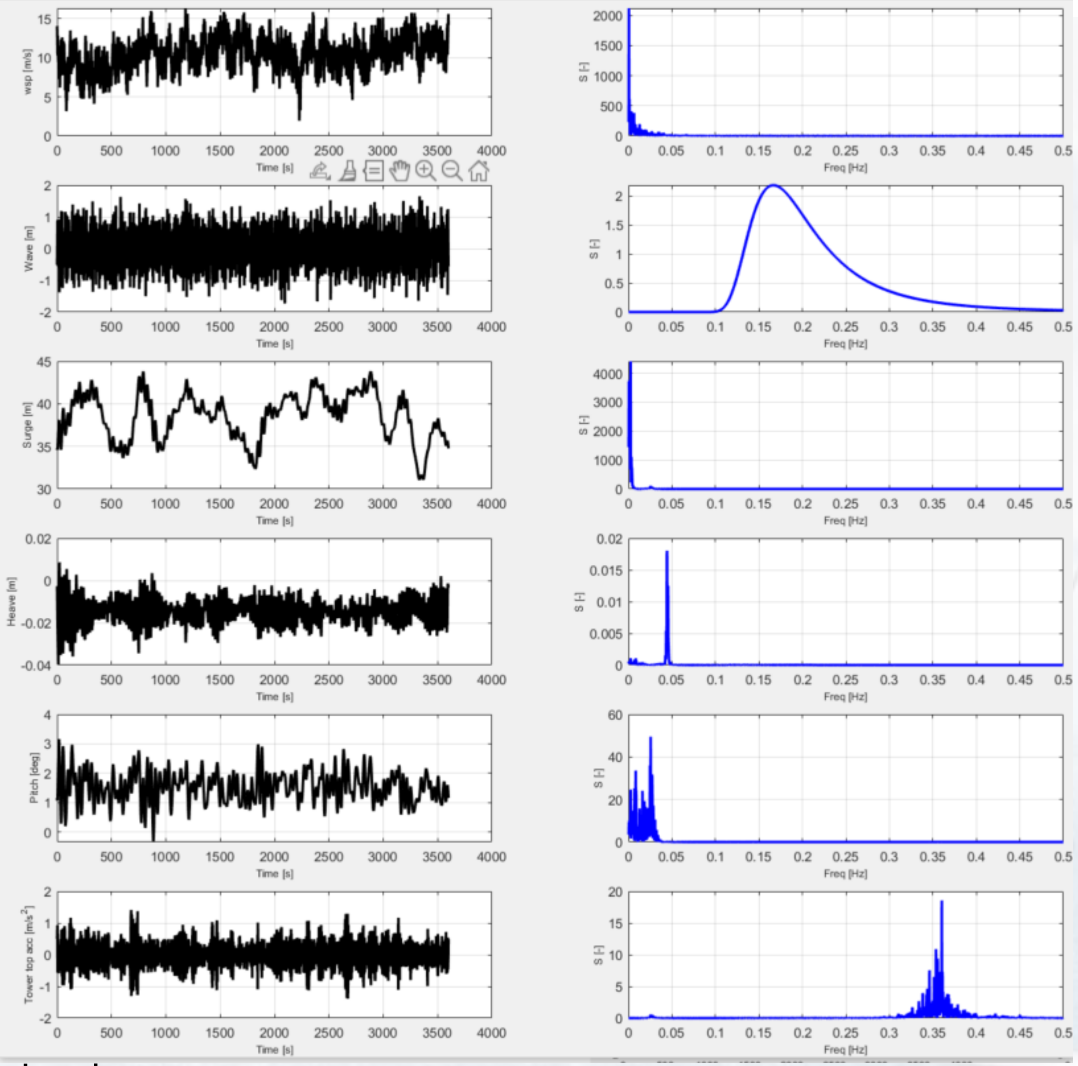
Optimized height of central column: 76.328 meter
Optimized diameter of central column: 5.005 meter
Optimized length of pontoon: 79.536 meter
Optimized diameter of pontoon: 10.000 meter
Optimized diameter of brace: 5.000 meter
Optimized diameter of horizontal brace: 10.000 meter
Optimized depth of keel from msl: -100.602 meter
Optimized depth of fairlead: -36.720 meter
Optimized anchor radius: 676.312 meter
Optimized mooring line length: 772.139 meter
cost: 84.1235

Nicoló Pollini ++

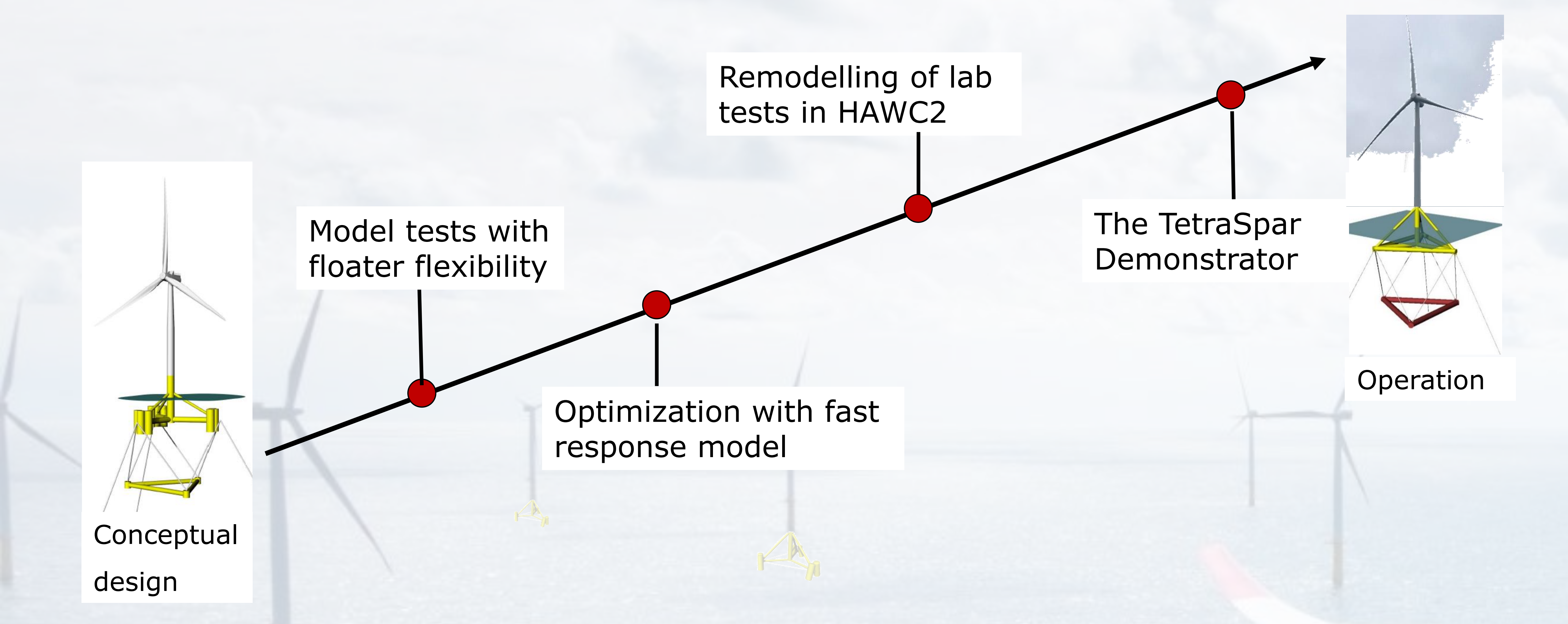
Initial results – no transient dynamic constraints





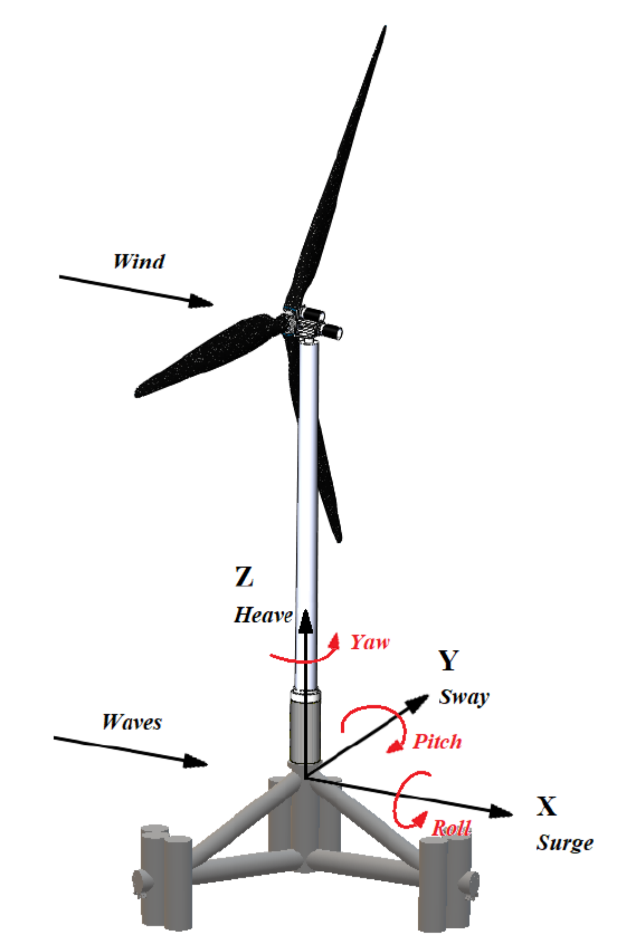


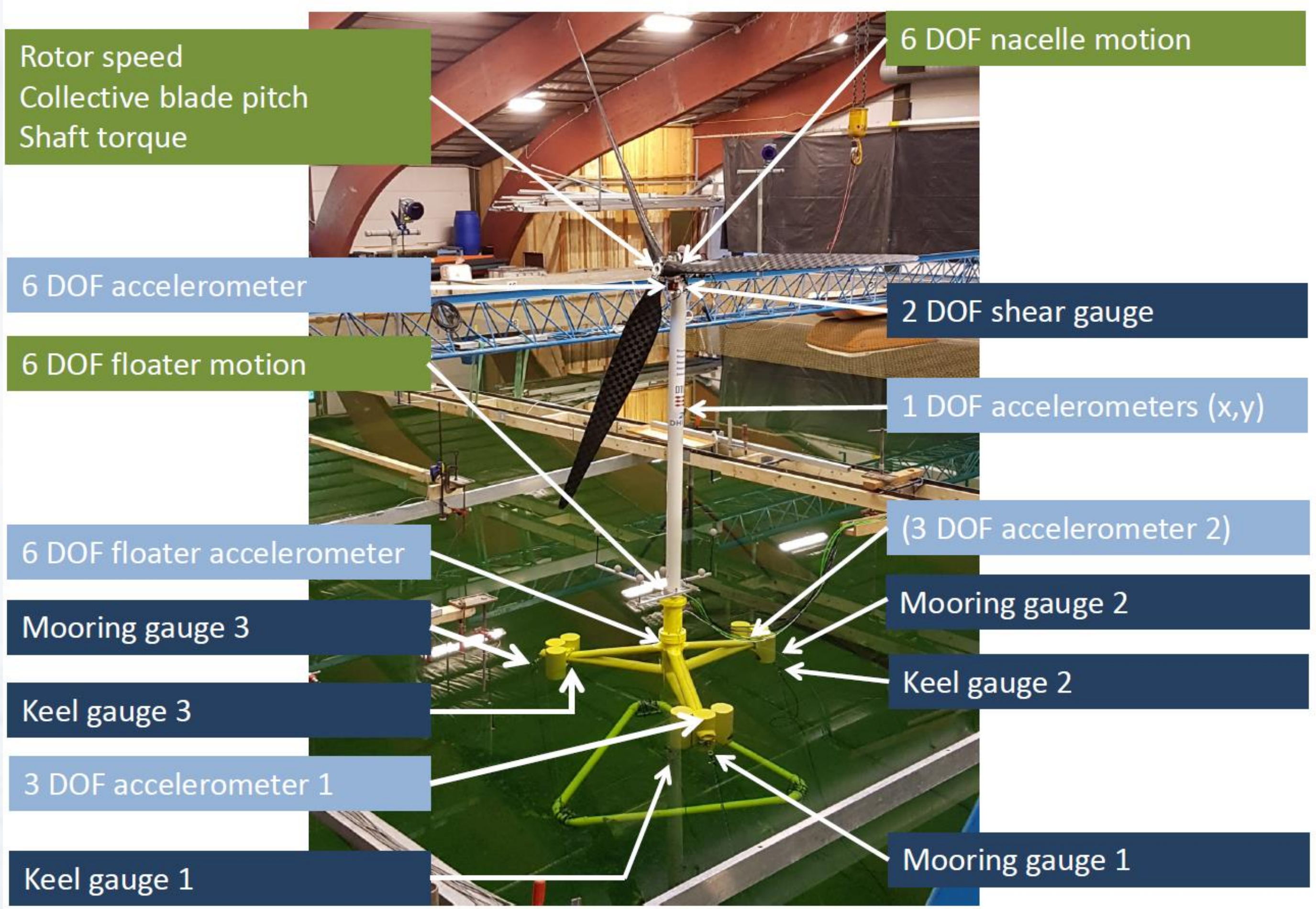
Validated and efficient design tools



Innovation Fund Denmark

Validation of HAWC2 for 2017 TetraSpar proof of concept tests





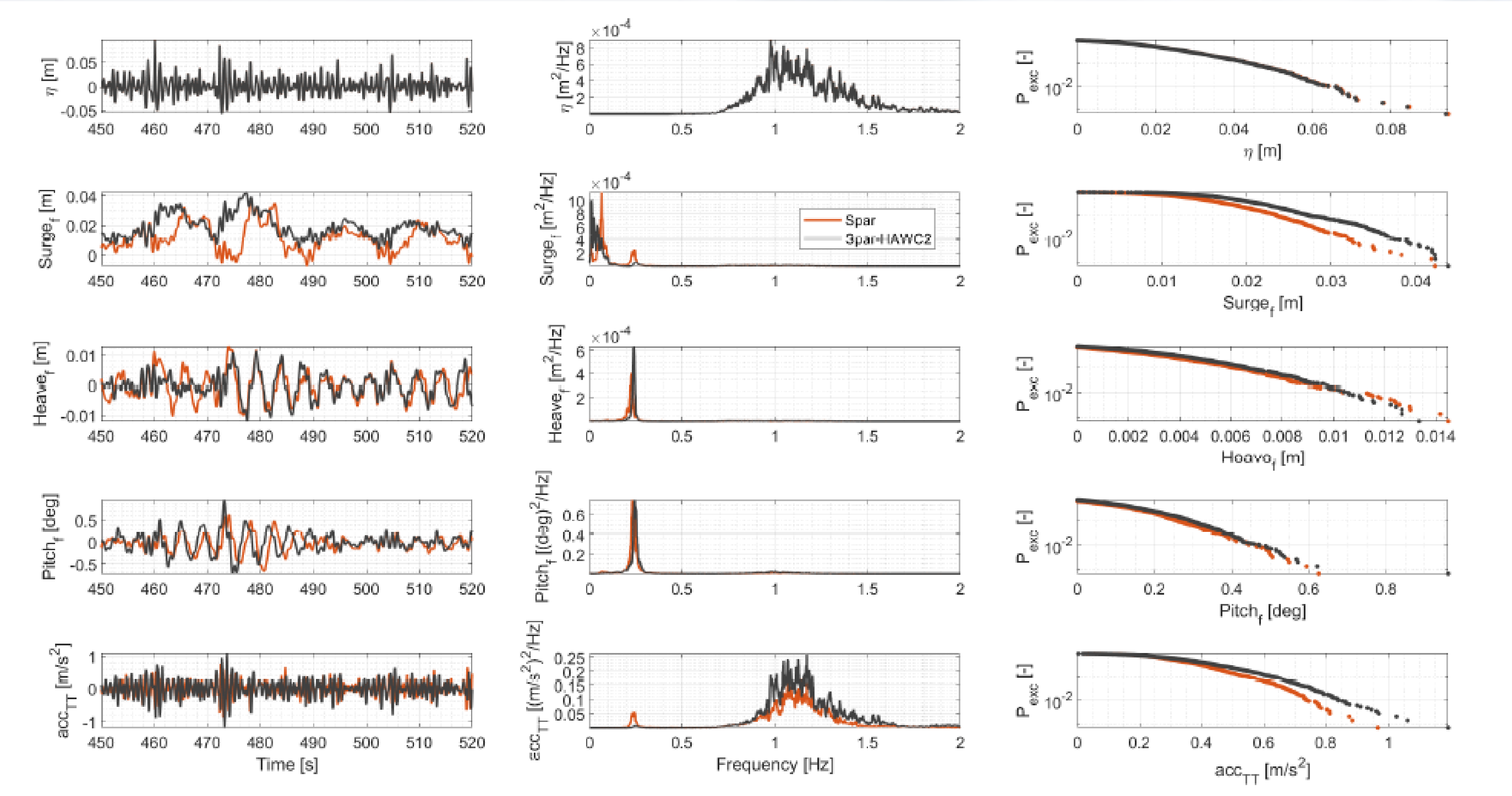
FloatStep – Science and innovation for floating wind technology

Borg et al (2018 – EERA DeepWind; 2022)

Wave state of rated wind speed

Wamit, Newman, relative Morison drag, calibrated damping

Innovation Fund Denmark



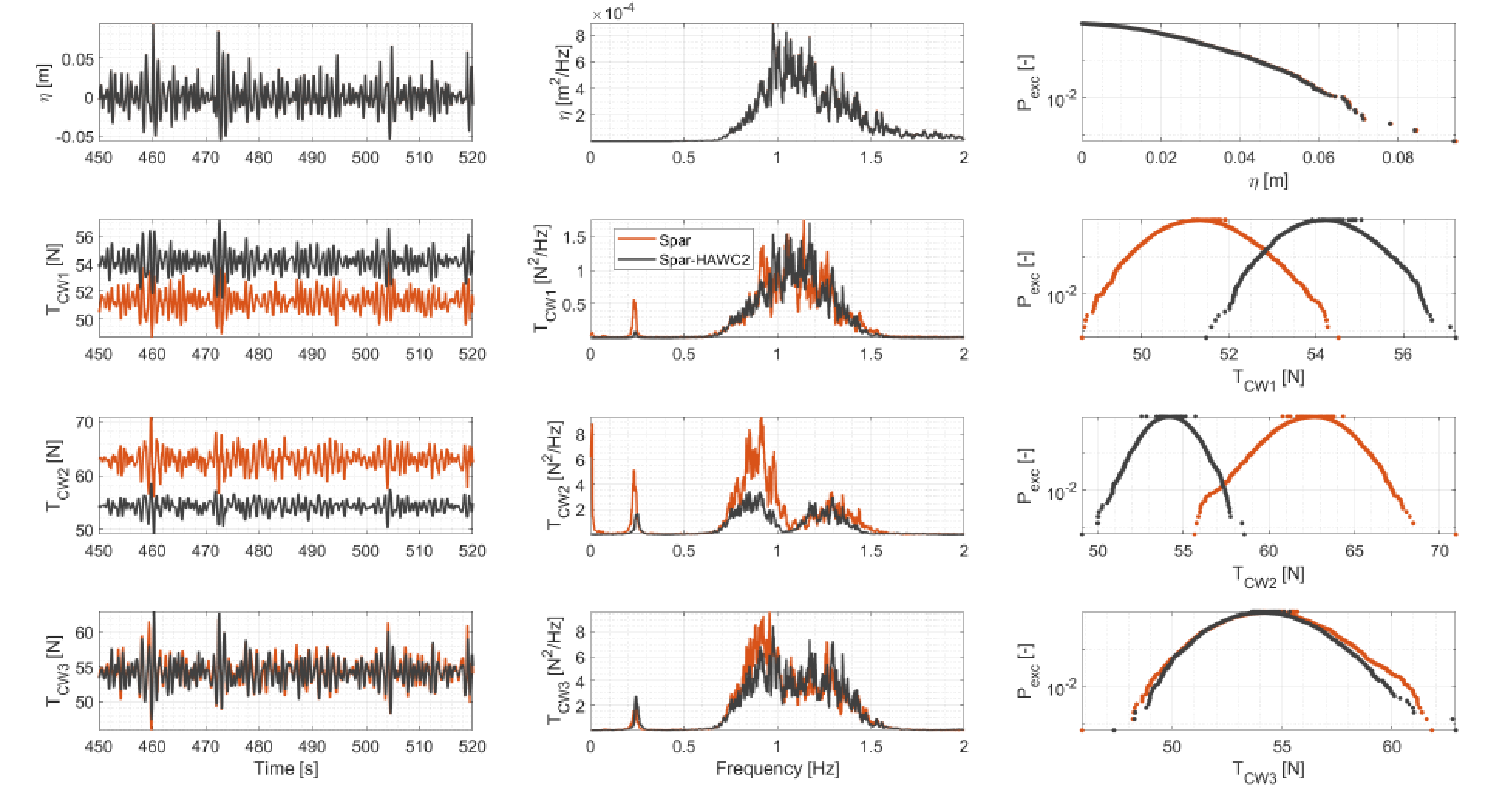
Good reproduction for inline floater motion and tower top acceleration.

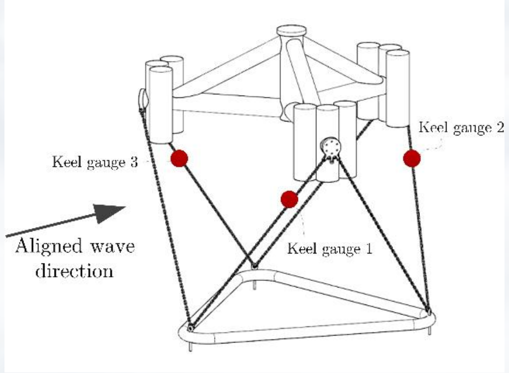
Borg, Pegalajar-Jurado et al (2022)

Wave state of rated wind speed

Innovation Fund Denmark

Wamit, Newman, relative Morison drag, calibrated damping





Keel line 1 tension OK except offset in pre-tension

Some difference for line 2 (but good in storm sea state, not shown here)

Line 3 perfect

Borg, Pegalajar-Jurado et al (2022)

Ongoing: Remodelling of TetraSub concept tests 2021

A variant of the TetraSub concept was tested with the scaled DTU 10 MW turbine in the spring of 2021

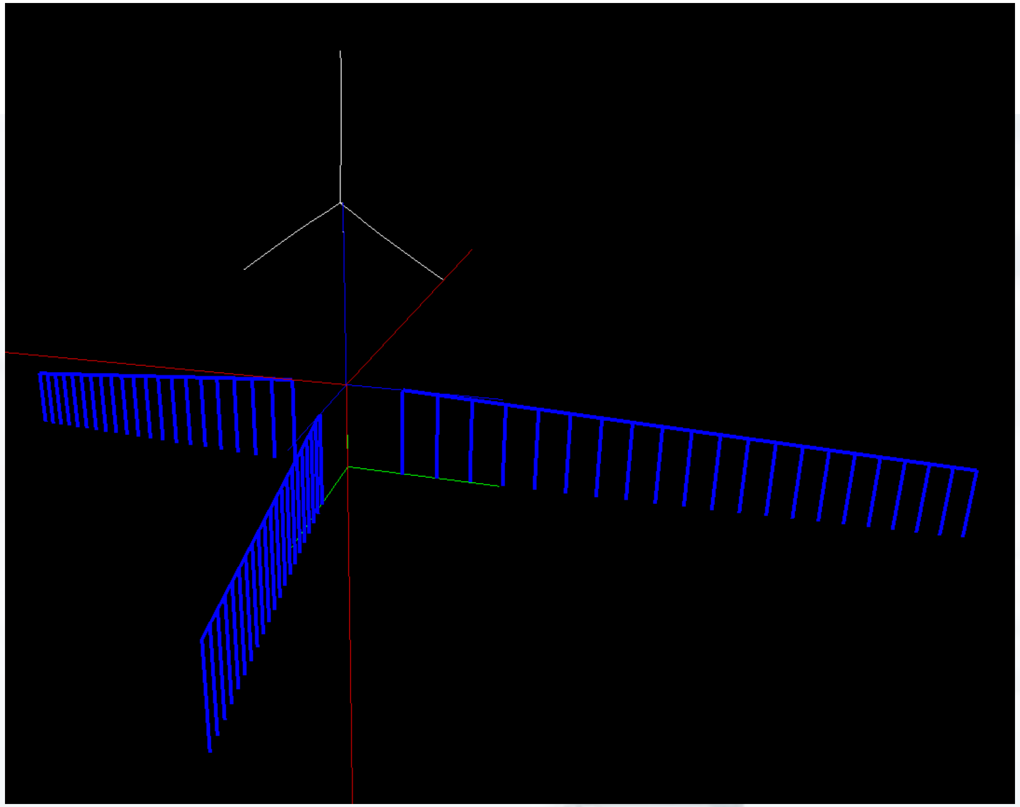
Stiesdal Offshore Technologies

DHI

DTU

Re-modelling in HAWC2

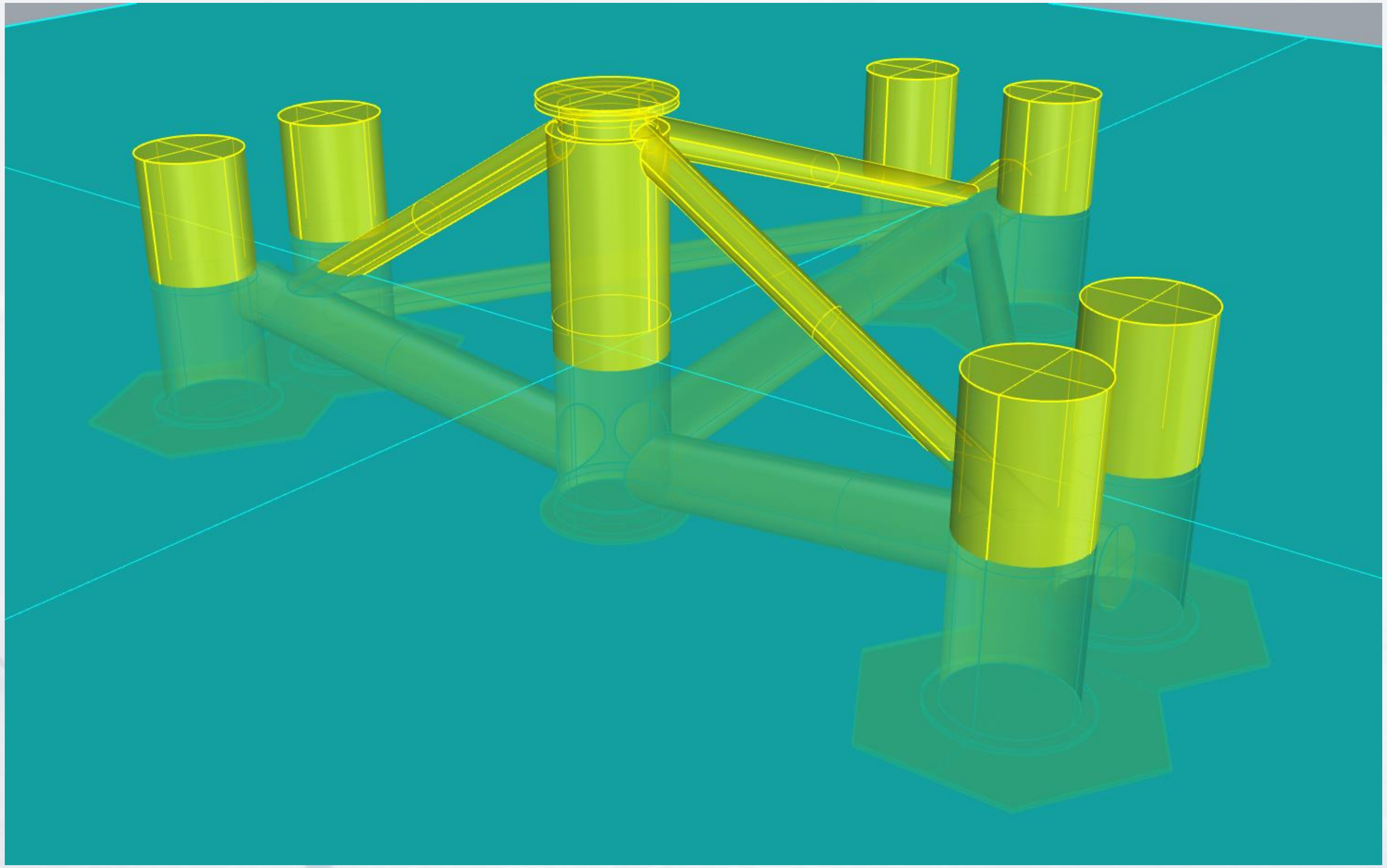
- Model in 1:60 scale
- Turbine model from previous campaigns
- Floater modelled in WAMIT to obtain
  - Added mass and damping
  - Hydrostatic properties
  - Wave load transfer functions
- No viscous effects yet



Antonio Pegalajar-Jurado

WAMIT analysis of tested TetraSub floater

- CAD geometry v3: right draft

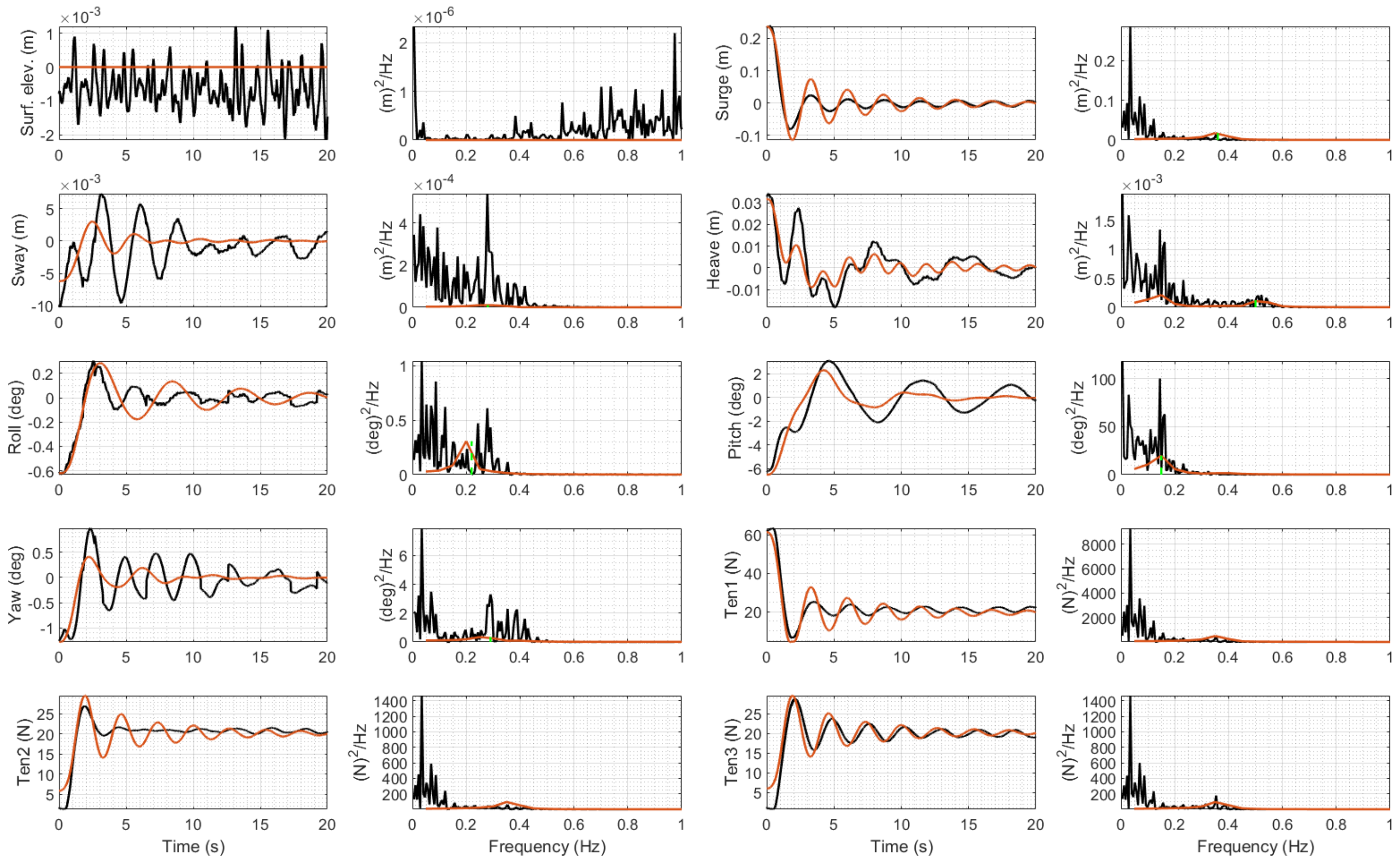


DTU

Stiesdal Offshore Technologies

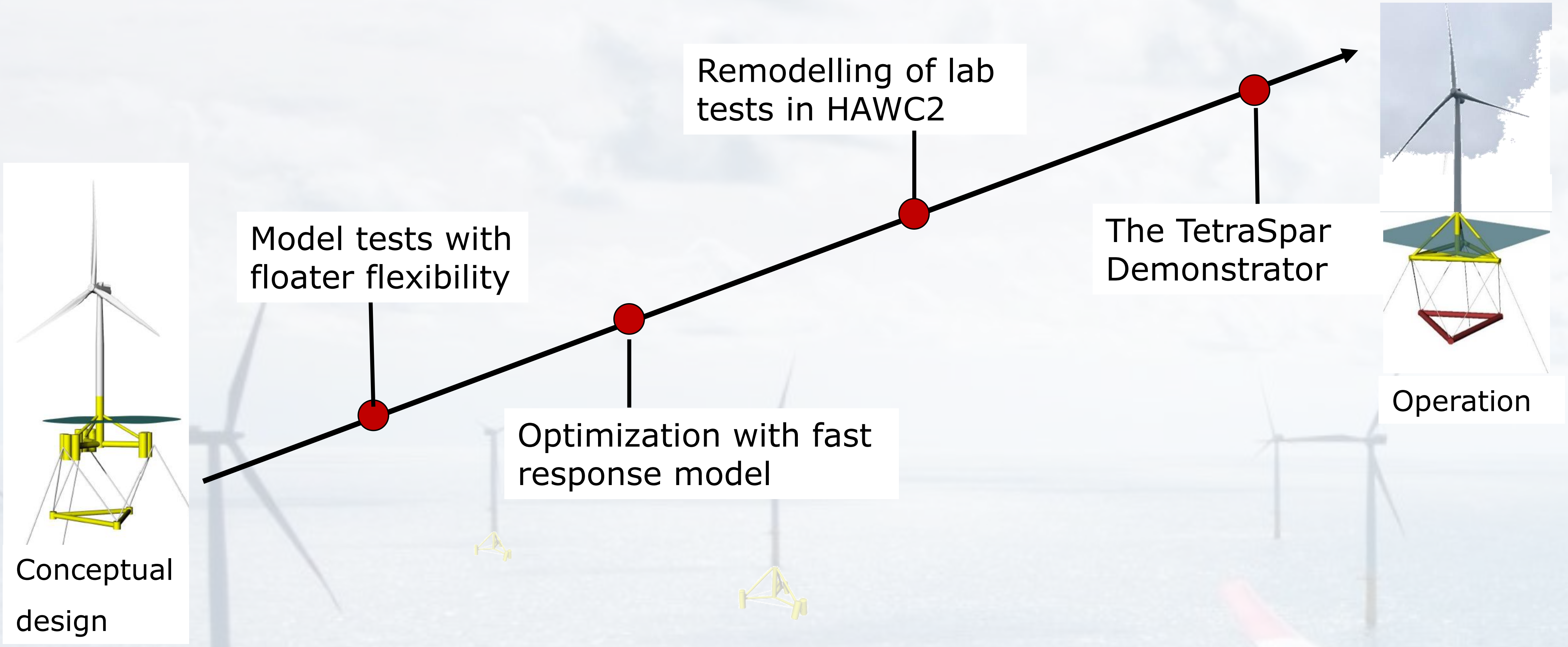
Innovation Fund Denmark

HAWC2 model – surge decay



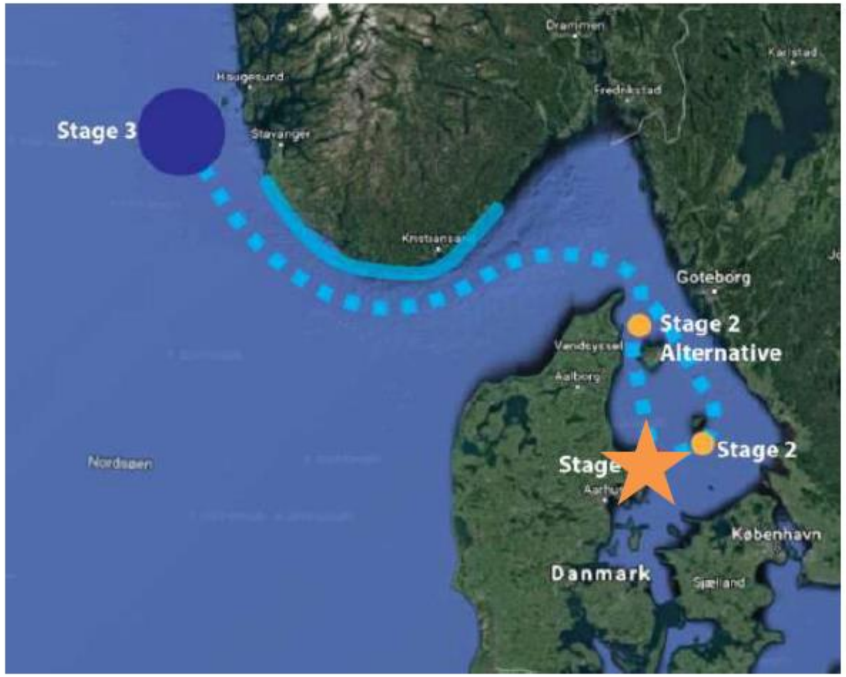
Innovation Fund Denmark

Validated and efficient design tools



TetraSpar Demonstrator installed 2021

Prototype with 3.6 MW SGRE turbine
Installed at the MetCentre, Karmøy, July 2021



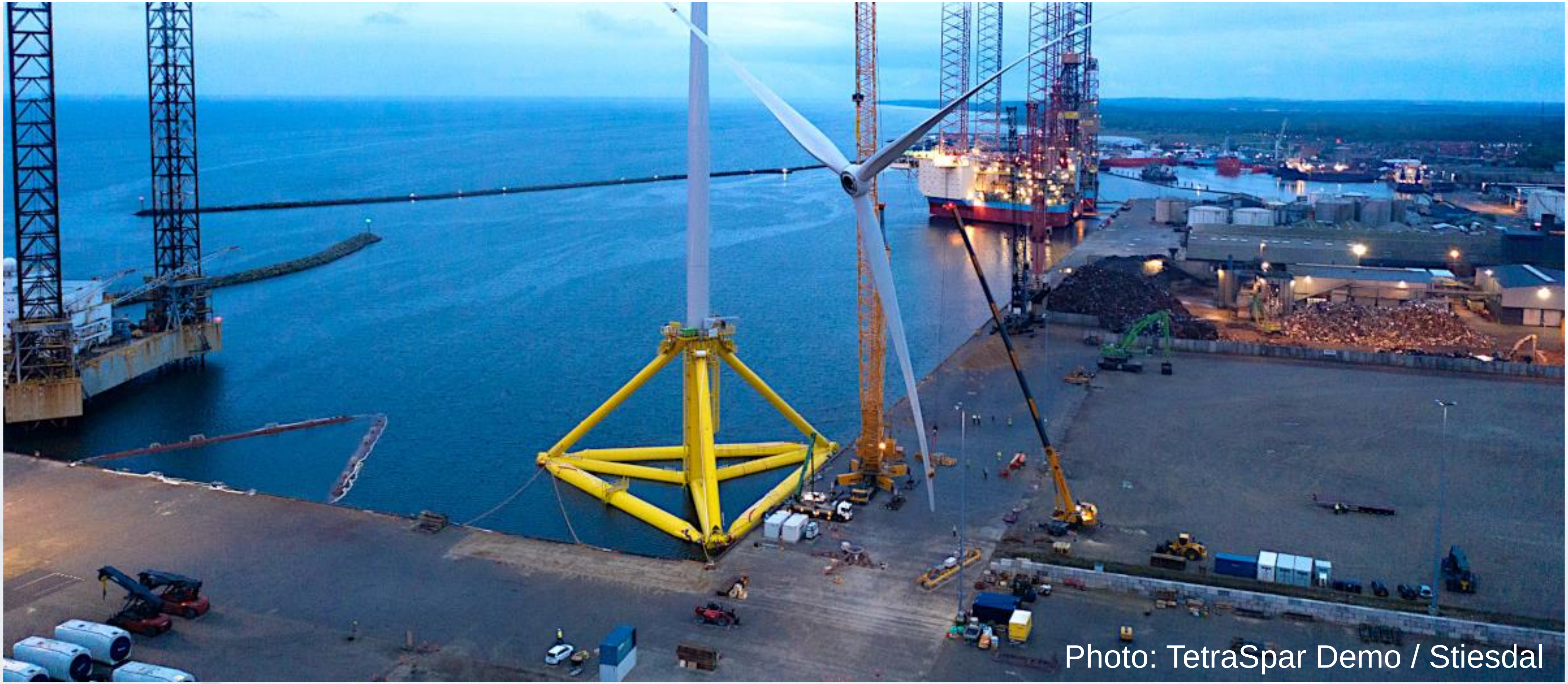
Stiesdal Offshore Technologies

Innovation Fund Denmark

Assembly of the TetraSpar Demonstrator 2021


Photo: TetraSpar Demo / Stiesdal

Rotor lift May 2021



Towing of the TetraSpar Demonstrator July 2021

Innovation Fund Denmark

Installation TetraSpar Demonstrator July 2021

Photo: TetraSpar Demo / Stiesdal

Installed! TetraSpar Demonstrator July 2021

Innovation Fund Denmark

Next steps in FloatStep

- Analysis of full scale data
- Analysis of model scale tests for blade pitch control
- OpenFOAM solver for floating structures

Publications of FloatStep

Madsen, Pegalajar-Jurado and Bredmose (2019) 'Performance study of the QuLAF pre-design model for a 10MW floating wind turbine', Wind Energy Science 4, pp 527-547.

H. Bredmose and A. Pegalajar-Jurado (2021) 'Second-order monopile wave loads at linear cost'. Coastal Engineering. **170** 103952

Orszaghova, J., Taylor, P. H., Wolgamot, H. A., Madsen, F. J., Pegalajar-Jurado, A. M., & Bredmose, H. (2021). Wave-and drag-driven subharmonic responses of a floating wind turbine. Journal of Fluid Mechanics, 929, 1402-1413.

Borg, M., Pegalajar-Jurado, A., Bredmose, H., Stiesdal, H., Madsen, F.J., Nielsen, T.R.L., Mikkelsen, R.F, Mirzaei, M. and Lomholt, A.K. (2022), 'Dynamic response analysis of the TetraSpar floater in waves: Experimental and numerical investigations'. In revision.

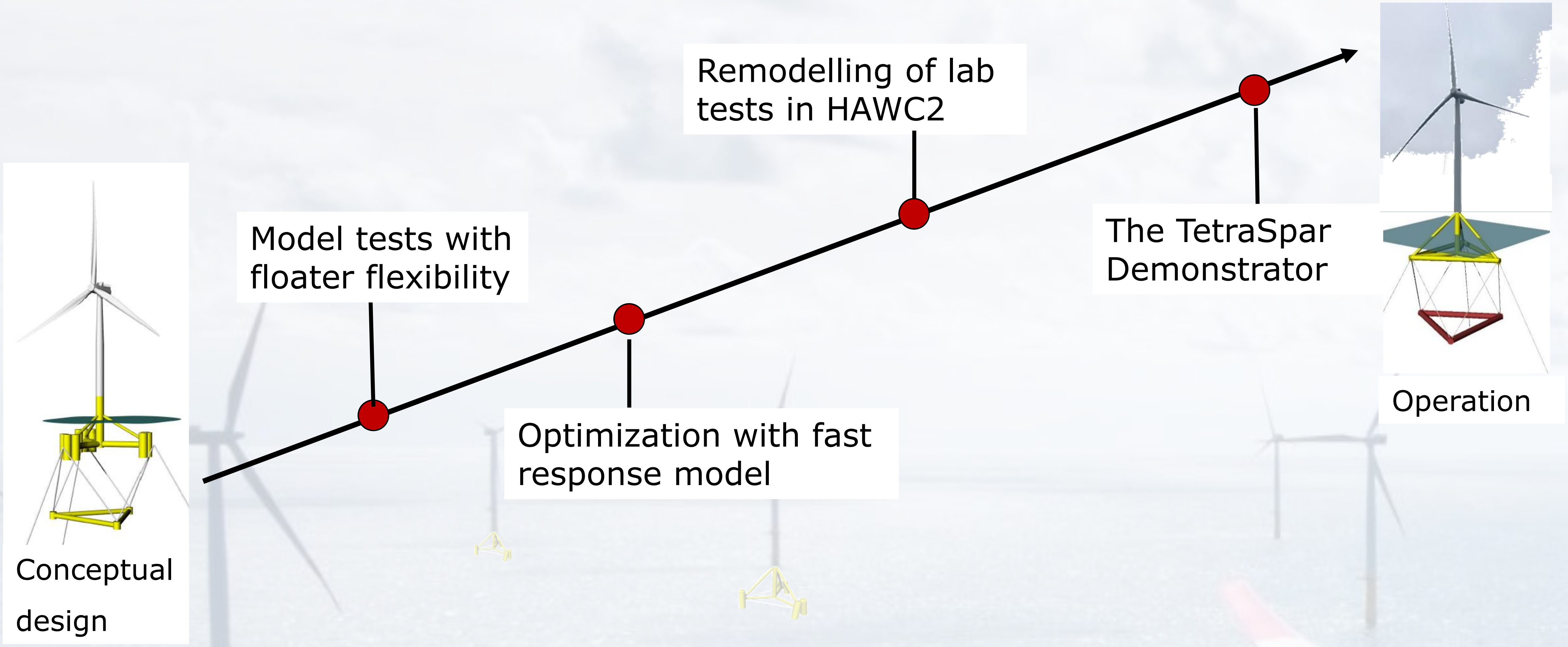
Pegalajar-Jurado, Madsen and Bredmose (2019) 'Damping identification of the TetraSpar floater in two configurations with Operational Modal Analysis'. 2nd Int Offshore Wind Technical Conference, Malta, November 2019. ASME.

Dou, S., Pegalajar-Jurado, A., Wang, S., Bredmose, H., & Stolpe, M. (2020). Optimization of floating wind turbine support structures using frequency-domain analysis and analytical gradients. Journal of Physics: Conference Series, 1618(4)

Pegalajar-Jurado, A. and Bredmose, H. (2020) 'Accelerated hydrodynamic analysis for spar buoys with second-order wave excitation'. 39th Int. Conf. Ocean Offshore Arctic Engng, OMAE 2020, Florida, June 2020.

Pollini, N., Pegalajar-Jurado, A., Dou, S., Bredmose, H., & Stolpe, M. (2021). Gradient-based optimization of a 15 MW wind turbine spar floater. Journal of Physics: Conference Series, 2018(1), [012032]. https://doi.org/10.1088/1742-6596/2018/1/012032

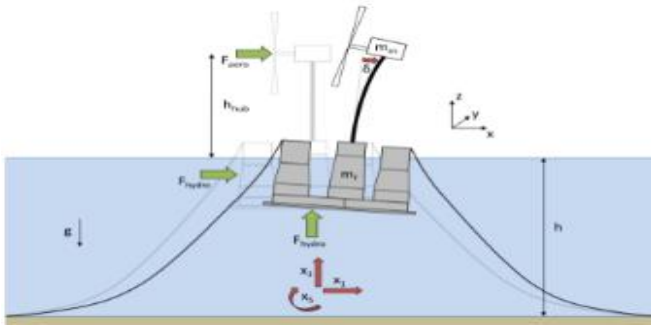
Validated and efficient design tools

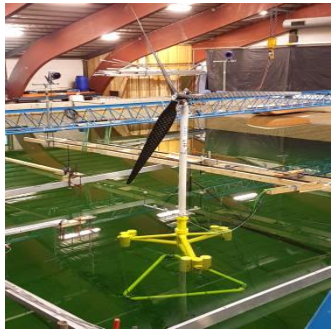


Innovation Fund Denmark

Accurate and validated design tools for floating wind turbine substructures

Recent results from the FloatStep project





Henrik Bredmose[1], Antonio Pegalajar-Jurado[1], Christine L. Hansen[1], Nicoló Pollini[1], Kasper Laugesen[2], Bjarne Jensen[3], Michael Borg[4], Johan Rønby[5], Jana Orszaghova[6]

DTU 1

SIEMENS Gamesa RENEWABLE ENERGY 2

DHI 3

Stiesdal Offshore Technologies 4

STROMNING 5

THE UNIVERSITY OF WESTERN AUSTRALIA 6