A Hardware-in-The-Loop System for Model Testing of Floating Offshore Wind Turbines in a Wind Tunnel

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 860737.

Agenda

- Why Model Testing?
- Model Testing Approaches
- Politecnico di Milano (PoliMi) Setup
- Numerical Modelling Approach
- Real-Time Simplifications
- Outlook

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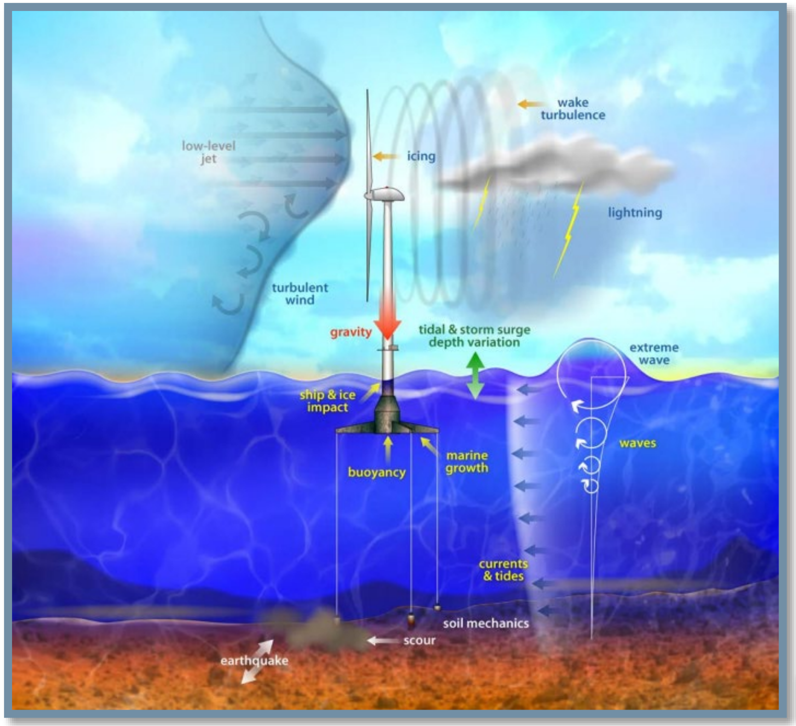
Why Model Testing?



[1]

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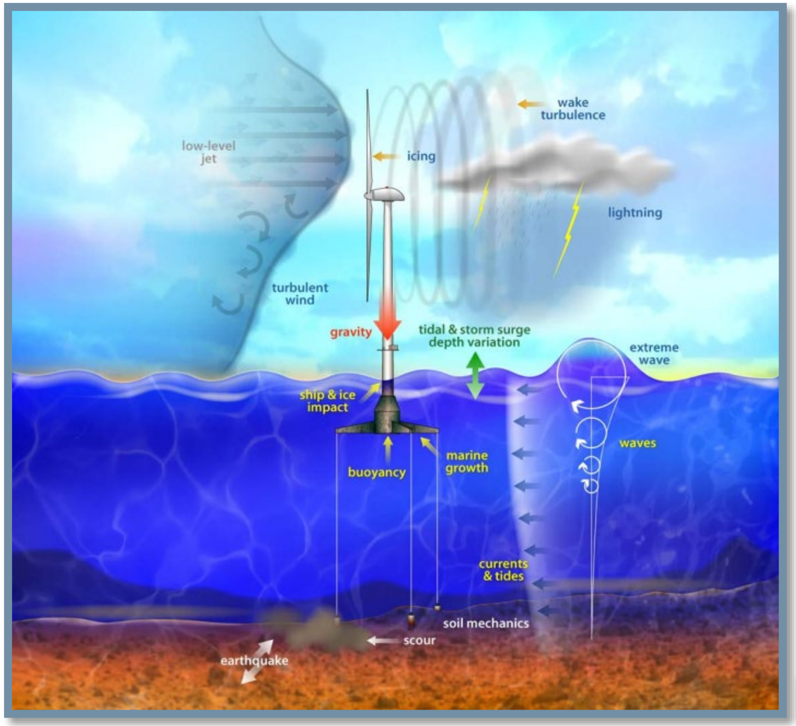
Why Model Testing?

OC5: several medium fidelity tools underpredicted ultimate and fatigue loads [2].

Financially unfeasible to build a prototype for testing purposes.



[1]

System response to physical loads vary according to platform and mooring design.

Only a few FOWTs were deployed. Lack of benchmark data.

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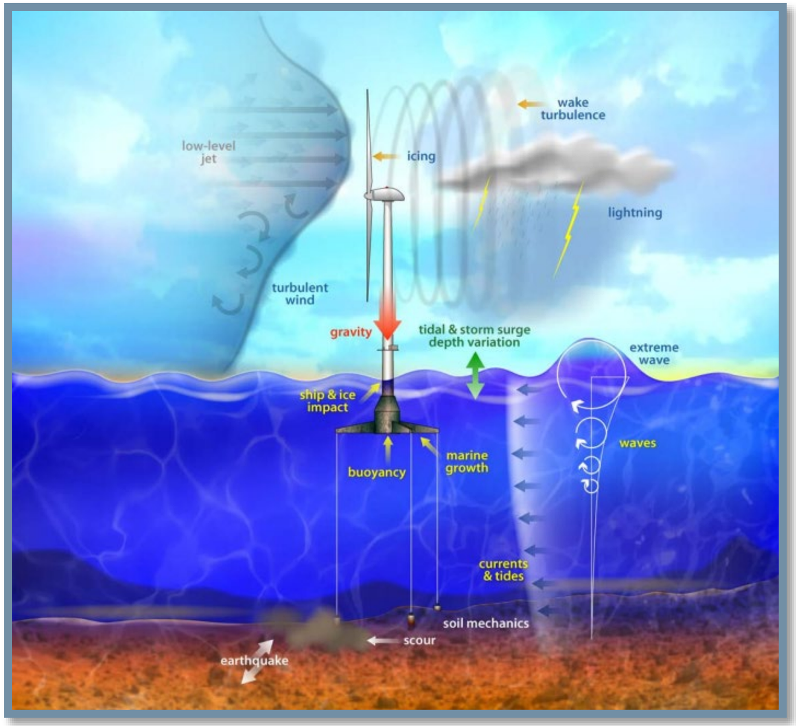

[1]

System response to physical loads vary according to platform and mooring design.

Only a few FOWTs were deployed. Lack of benchmark data.

Solution → Validate numerical models with HiL experiments

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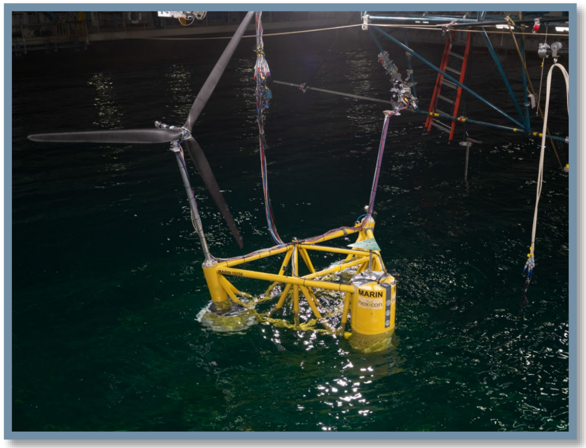
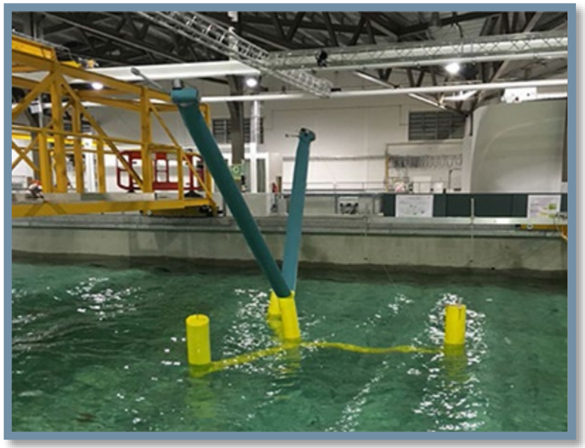
Why Model Testing?

Hexicon Prototype [3]



Hexicon Model Test at MARIN [4]



aerodyn SCDneezy2 1:36 Model Test[5]

aerodyn SCDneezy2 1:10 Prototype [6]

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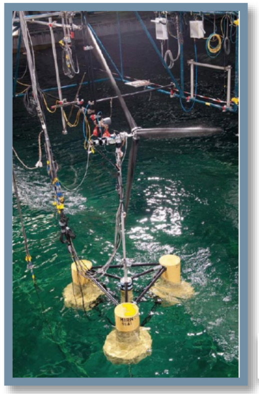
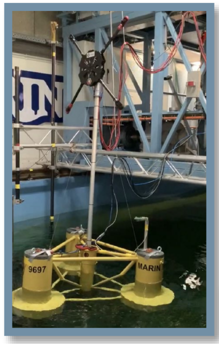
Model Testing Approaches

Full Approach

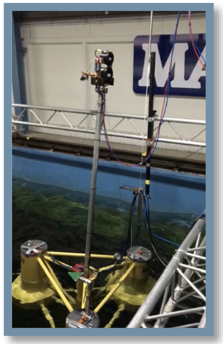


[7]

Hybrid Approach



[8]



[8]

[9]

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Model Testing Approaches

Full-Approach Testing of the TripleSpar at DTU [10]

- (+) Likely to capture unseen phenomena
- (-) Repeatability of the wind field
- (-) Blade scaling process
- (-) Versatility
- (-) Costly

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Model Testing Approaches

Wave Basin Hybrid Testing

Wind Tunnel Hybrid Testing

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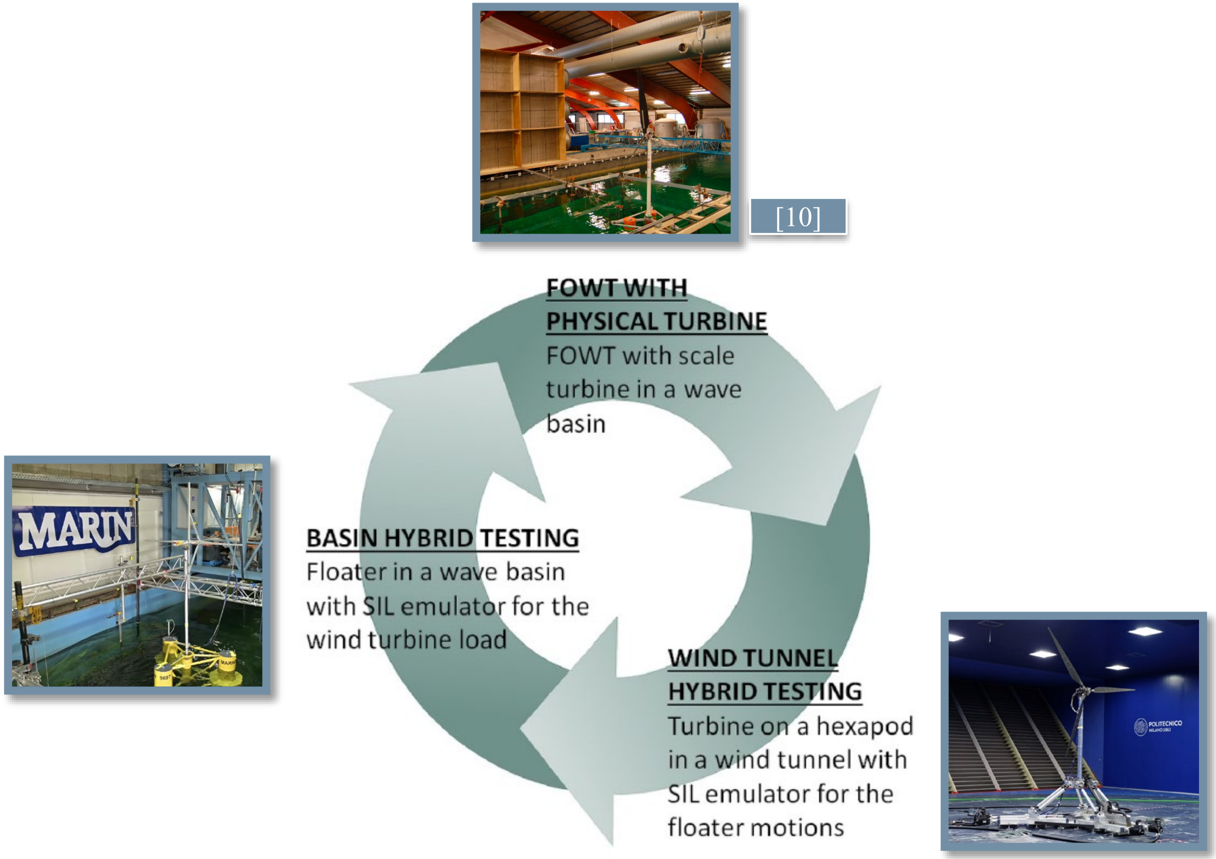
Model Testing Approaches



Complementarity of model testing methods [8].

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PoliMi Setup

HexaFloat and DTU 10 MW performance scaled rotor.

High quality wind field generated at the boundary layer section of the GPVM.

Allows testing of different mooring system and platform concepts.

Unsteady aerodynamics via imposed motion.

Wake characterization.

Test different control strategies.

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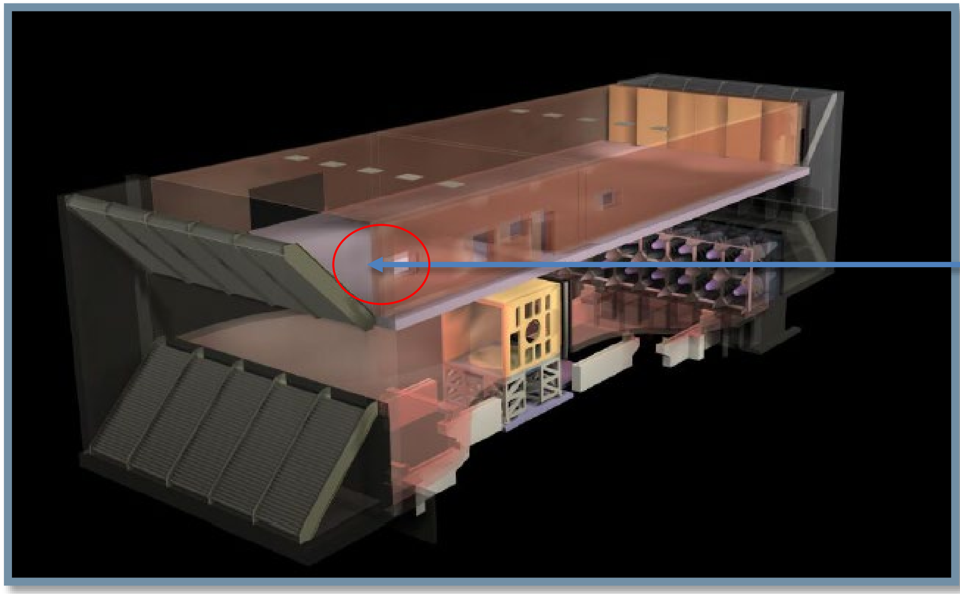
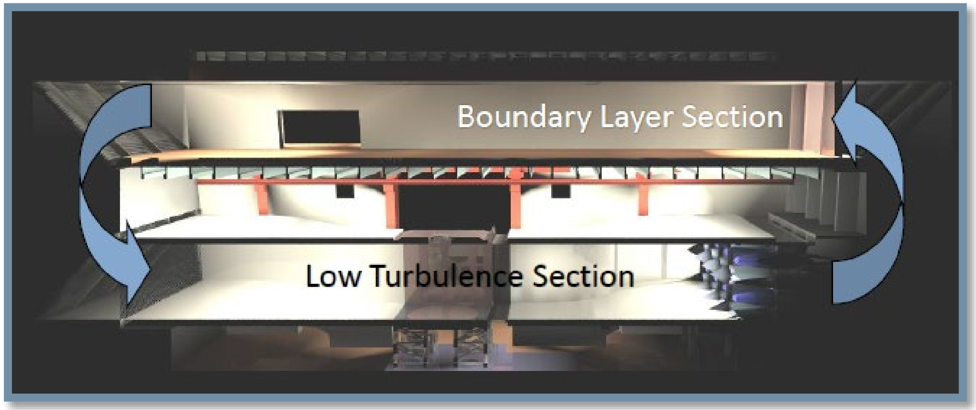
PoliMi Setup





Boundary Layer Section:
13,84m wide x 3,84m high x 35m long

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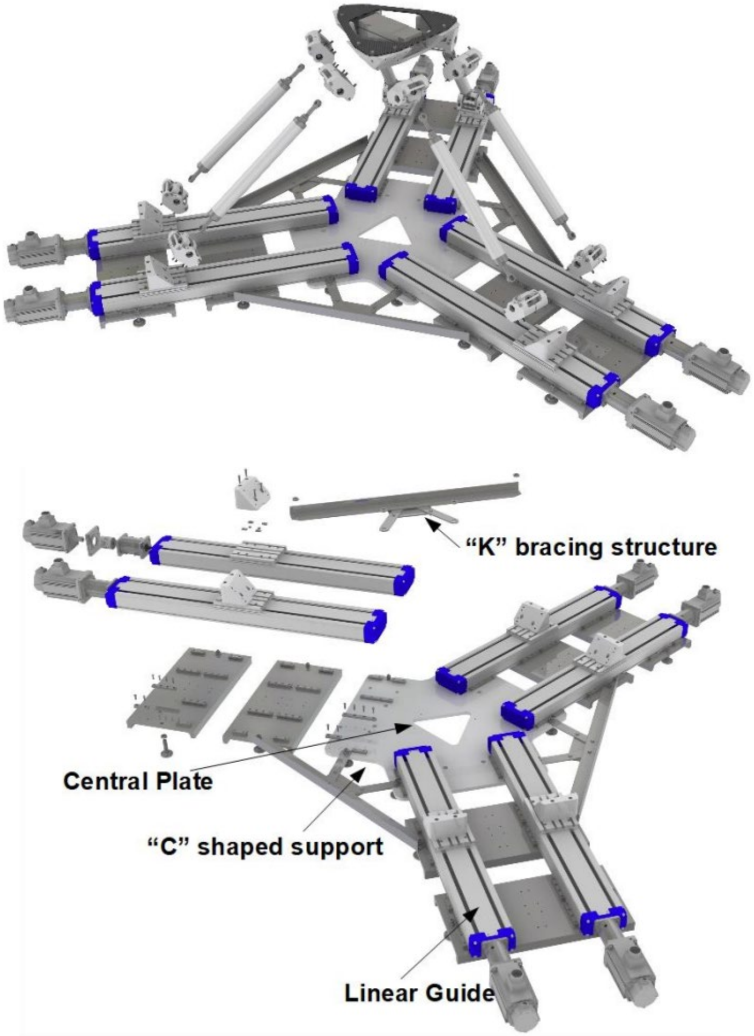
PoliMi Setup



HexaFloat 6-DOFs Parallel Kinematic Robot

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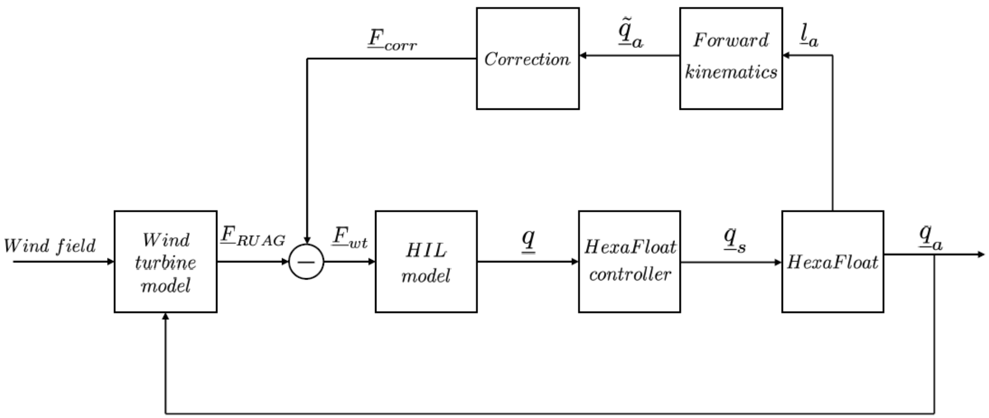
Setup Control Scheme



Control Scheme

$\underline{F}_{RUAG}$: Tower-base loads

$\underline{F}_{corr}$: Correction loads

$\underline{F}_{wt}$: Wind turbine loads

$\underline{q}_a$: Platform actual position

$\underline{q}_s$: Platform set-point

$\underline{\tilde{q}}_a$: Platform actual position estimate

$\underline{q}$: Platform position from HIL model

$\underline{l}_a$: HexaFloat actuators actual position

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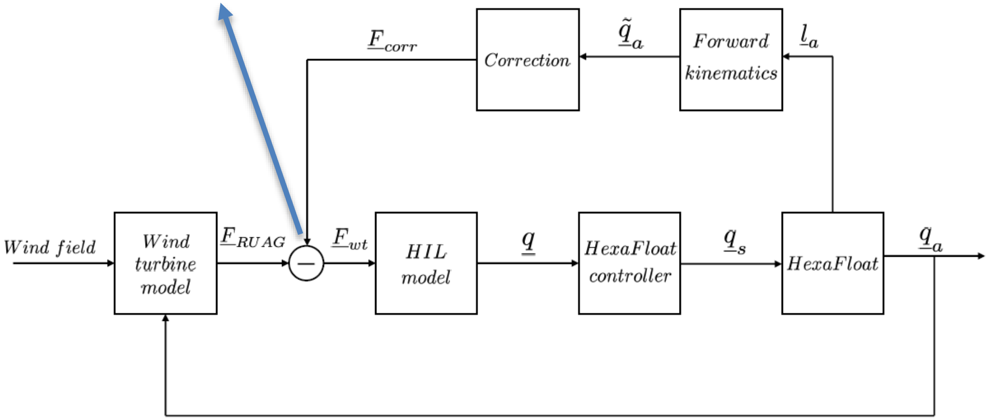
Setup Control Scheme

$$\underline{F}_{wt} = \underline{F}_{RUAG} - \underline{F}_{corr} \rightarrow \underline{F}_{corr} = [M_t]\dot{\underline{\tilde{q}}}_a + [K_t]\,\underline{\tilde{q}}_a$$



Control Scheme

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Numerical Modelling Approach

$$[M_s + A_\infty]\underline{\ddot{x}} + [R_s]\underline{\dot{x}} + [K_s]\underline{x} = \underline{F}_{wt} + \underline{F}_{plat}$$

I. Platform and Turbine Inertia Tensor

II. Platform Added Damping

III. Platform and Turbine Gravitational and Restoring Loads

IV. Aerodynamic Forces $\underline{F}_{wt} = \underline{F}_{a,rot} + \underline{F}_{a,tow} + \underline{F}_{gyro} + \underline{F}_{m,rot}$

V. Hydrodynamic Forces $\underline{F}_{plat} = \underline{F}_{rad} + \underline{F}_{we} + \underline{F}_{moor} + \underline{F}_{visc}$

- Radiation forces
- Wave forces
- Mooring forces
- Viscous forces

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I. Platform and Turbine Inertia Tensor

II. Platform Added Damping

Infinite-frequency hydrodynamic added mass matrix

III. Platform and Turbine Gravitational and Restoring Loads

IV. Aerodynamic Forces $\underline{F}_{wt} = \underline{F}_{a,rot} + \underline{F}_{a,tow} + \underline{F}_{gyro} + \underline{F}_{m,rot}$

Mass matrix of the global floating system

V. Hydrodynamic Fo ... $or + \underline{F}_{visc}$

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I. Platform and Turbine Inertia Tensor

II. Platform Added Damping

III. Platform and Turbine Gravitational and Restoring Loads

IV. Aerodynamic Forces

Structural damping matrix

V. Hydrodynamic Forces $\underline{F}_{plat} = \underline{F}_{rad} + \underline{F}_{we} + \underline{F}_{moor} + \underline{F}_{visc}$

- Radiation forces
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V. $\underline{F}_{rad} + \underline{F}_{we} + \underline{F}_{moor} + \underline{F}_{visc}$

Structural stiffness matrix

- Radiation forces
- Wave forces
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- Viscous forces

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Numerical Modelling Approach

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→ Requires simplifications to run in real-time

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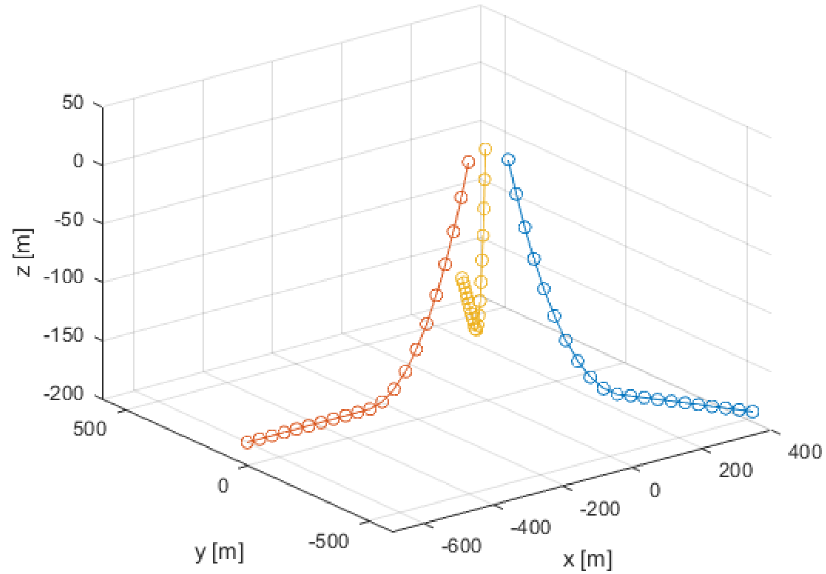
Numerical Modelling Approach

MoorDyn Lumped-Elements Model



$$M[(\underline{r})]\ddot{r} = \underline{F}(\underline{r}, \underline{\dot{r}})$$

$$M[(\underline{r})] = [m] + [a(\underline{r})]$$

$$\underline{F}(\underline{r}, \underline{\dot{r}}) = \underline{T}_{i+1/2}(r) - \underline{T}_{-1/2}(r) + \underline{C}_{i+1/2}(\underline{\dot{r}}, \underline{r}) - \underline{C}_{i-1/2}(\underline{\dot{r}}, \underline{r}) + \underline{W_i} + \underline{B_i}(\underline{\dot{r}}, \underline{r}) + \underline{D_{pi}}(\underline{\dot{r}}) + \underline{D_{qi}}(\underline{\dot{r}})$$

$\underline{T}$: *Tensile Loads*

$\underline{C}$: Damping

$\underline{W}$: Weight

$\underline{D_p}$: Viscous transverse damping

$\underline{D_q}$: Viscous tangential damping

$\underline{B_i}$: Seabed contact

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Real-Time Simplifications

I. Radiation forces.

II. Number of harmonics considered in the spectrum of the irregular sea state simulations.

III. Number of elements dividing the substructure $\underline{F}_{visc}$.

IV. Number of nodes composing the mooring lines.

V. the choice of specific contributions in terms of forces to be considered from the internal nodes of the catenary.

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Real-Time Simplifications

I. Radiation forces. → Approximation of the convolution term in the Cummins Equation. SSfitting toolbox

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Real-Time Simplifications

I. Radiation forces. → Approximation of the convolution term in the Cummins Equation. SSfitting toolbox

II. Number of harmonics considered in the spectrum of the irregular sea state simulations. → Decrease frequency resolution

III. Number of elements dividing the substructure $\underline{F}_{visc}$.

IV. Number of nodes composing the mooring lines.

V. the choice of specific contributions in terms of forces to be considered from the internal nodes of the catenary.

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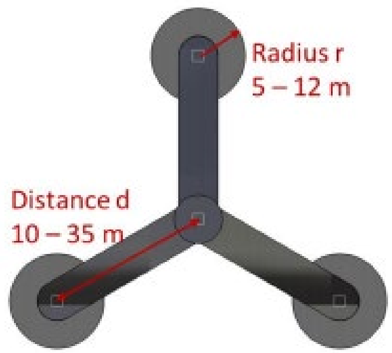
Real-Time Simplifications

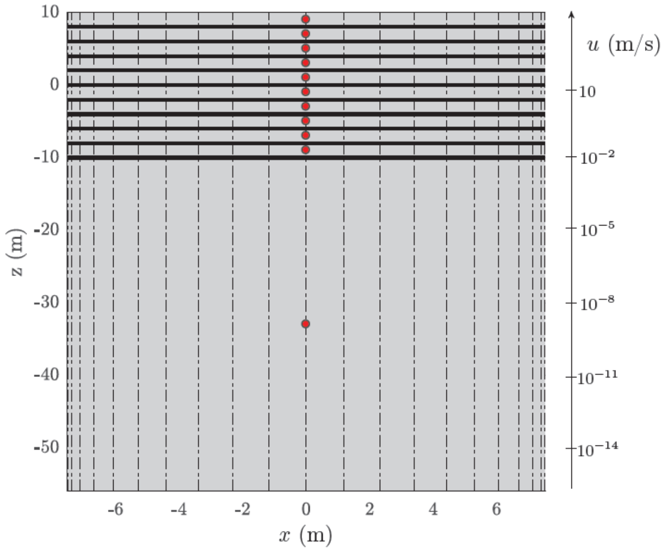
Viscous Forces

$$f_t(z,t) = \frac{1}{2} C_D D \left| v_{rel,t} \right| v_{rel,t}$$

$$f_{rad}(z,t) = \frac{1}{2} C_D D \left| v_{rel,rad} \right| v_{rel,rad}$$

$$f_{ax}(z,t) = \frac{1}{2} C_{ax} \pi \frac{D^2}{4L} \left| v_{rel,ax} \right| v_{rel,ax}$$





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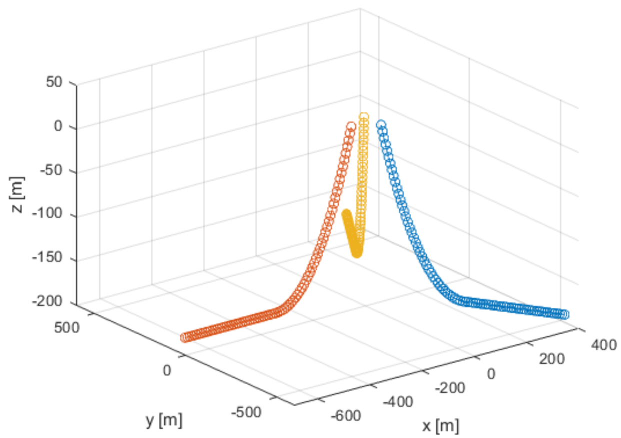
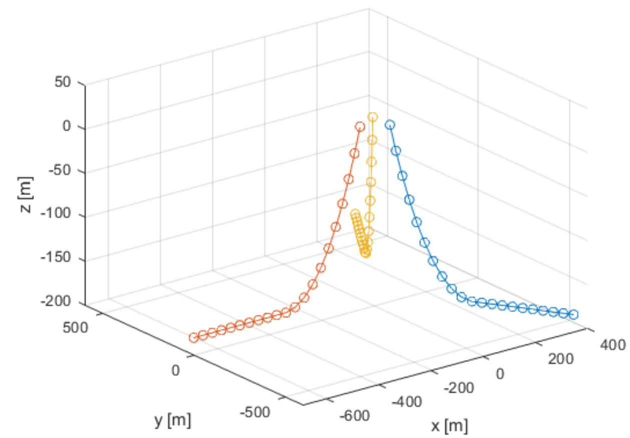
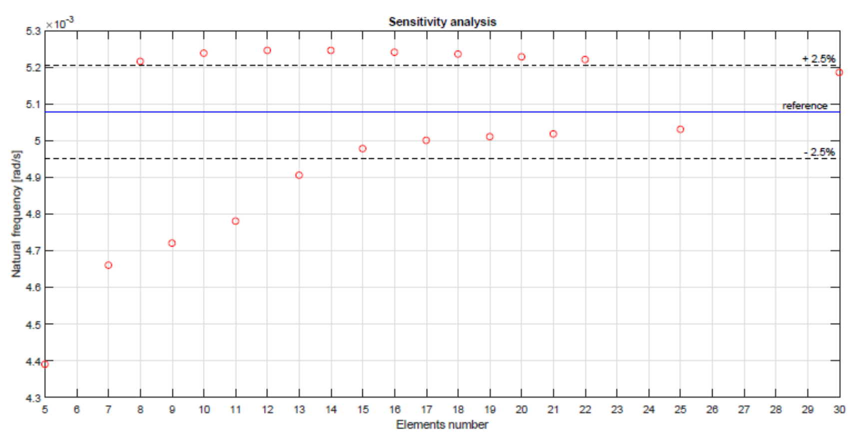
Real-Time Simplifications

Mooring Lines







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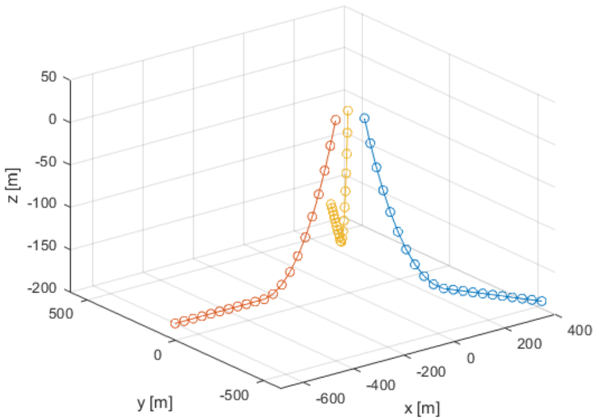
Real-Time Simplifications



Mooring Lines

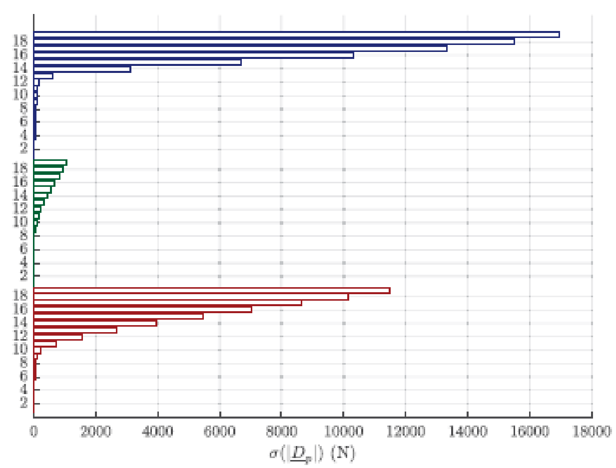
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
$\underline{M}$	△	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	△
$\underline{T}$	△	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	△
$\underline{C}$	△	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	△
$\underline{D}_p$	△	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	△
$\underline{D}_q$	△	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	△
$\underline{B}$	△	—	—	—	—	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	△

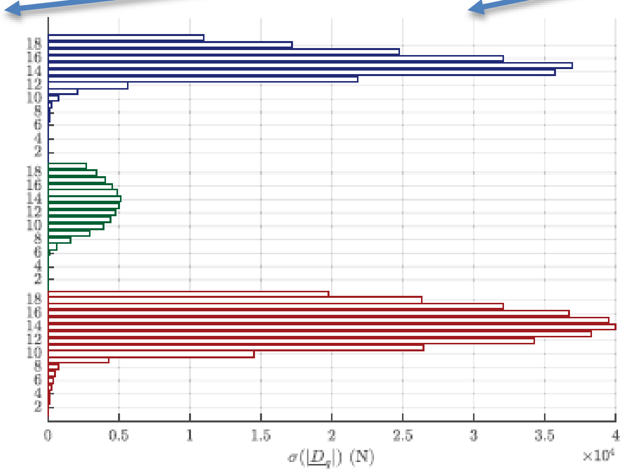
$\underline{D}_p$: Viscous transverse damping

$\underline{D}_q$: Viscous tangential damping

$$\underline{F}(\underline{r},\underline{\dot{r}}) = \underline{T}_{i+1/2}(r) - \underline{T}_{-1/2}(r) + \underline{C}_{i+1/2}(\underline{\dot{r}},\underline{r}) - \underline{C}_{i-1/2}(\underline{\dot{r}},\underline{r}) + \underline{W}_i + \underline{B}_i(\underline{\dot{r}},\underline{r}) + \underline{D}_{pi}(\underline{\dot{r}}) + \underline{D}_{qi}(\underline{\dot{r}})$$

Combined Decay





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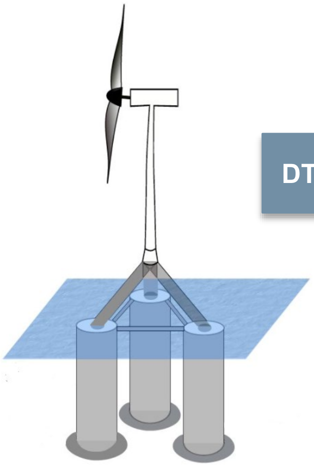
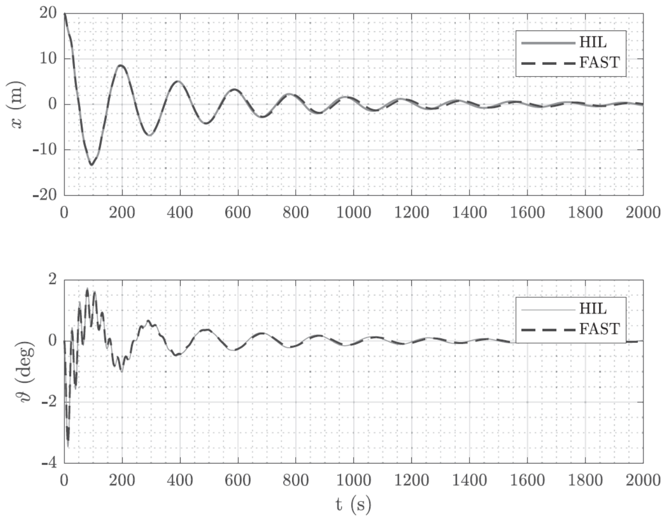
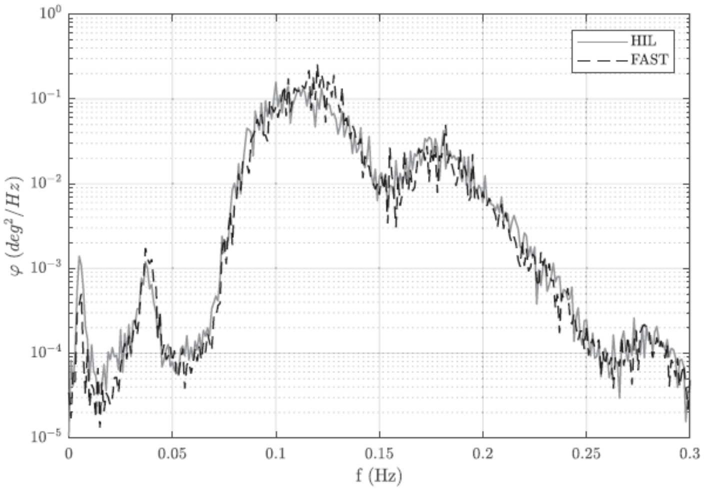
Comparison of the Experiments with Numerical Simulations

	f (Hz) HIL	f (Hz) FAST	p HIL	p FAST	q HIL	q FAST
Surge	0.0052	0.0050	0.24	0.28	0.039	0.033
Sway	0.0049	0.0049	0.26	0.30	0.034	0.028
Heave	0.0628	0.0628	0.31	0.31	0.015	0.015
Roll	0.0360	0.0361	0.38	0.32	-0.059	-0.018
Pitch	0.0380	0.0380	0.35	0.29	-0.037	0.001
Yaw	0.0130	0.0130	0.10	0.10	0.014	0.017



DTU 10MW TripleSpar [10]





Experimental Results [11]

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Outlook

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Grazie!

Questions?

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[1] Jonkman, J. *Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine*. NREL/TP-500-41958. Golden, CO: National Renewable Energy Laboratory, 2007.
[2] Amy Robertson et Al. *OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floatin Semisubmersible Wind Turbine.* 2017.
[3] Hexicon Prototype. Photo taken from: https://cleantechnica.com/2021/05/17/one-floating-wind-turbine-good-two-floating-wind-turbines-better/
[4] MARIN Model Test. Photo taken from: https://www.offshorewind.biz/2021/06/21/hexicon-completes-model-test-for-its-two-turbine-floater/
[5] Cian J. Desmond et Al. *Uncertainty in the Physical Testing of Floating Wind Energy Platforms' Accuracy versus Precision.* 2019.
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