The Triple Spar campaign: Experiments with a floating wind turbine in wind, waves and blade pitch control

Henrik Bredmose, Frank Lemmer, Michael Borg, Antonio Pegalajar Jurado, Robert Mikkelsen, Troels Stoklund Larsen, Tobias Fjeldstrup, Yu Wei, Anders Kjær Lomholt, Lasse Boehm, José Azcona Armendariz

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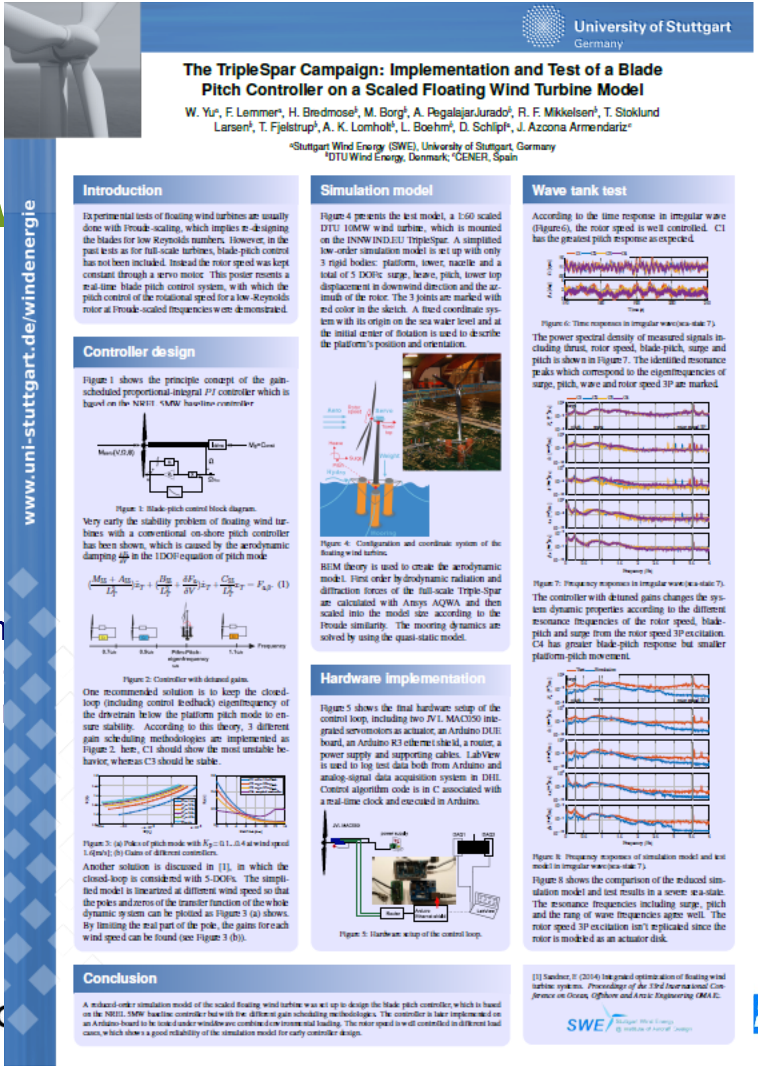
The Triple Spar campaign: Experiments with a floating w waves and blade pitch contro



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Floating wind turbine tests

DeepCWind consortium

Marin + ECN

Ulsan

Mitsubishi Heavy Industries

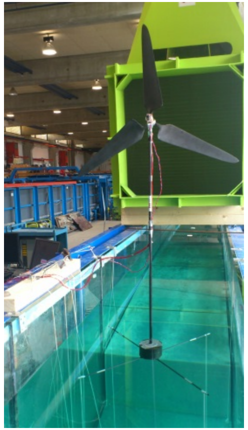
University of Maine

Marintek

DTU

University of Stuttgart

Politecnico di Milano



Hansen et al (2014)

Sandner et al (2015)

Bredmose et al (2015)
Pegalajar-Jurado et al (2016)

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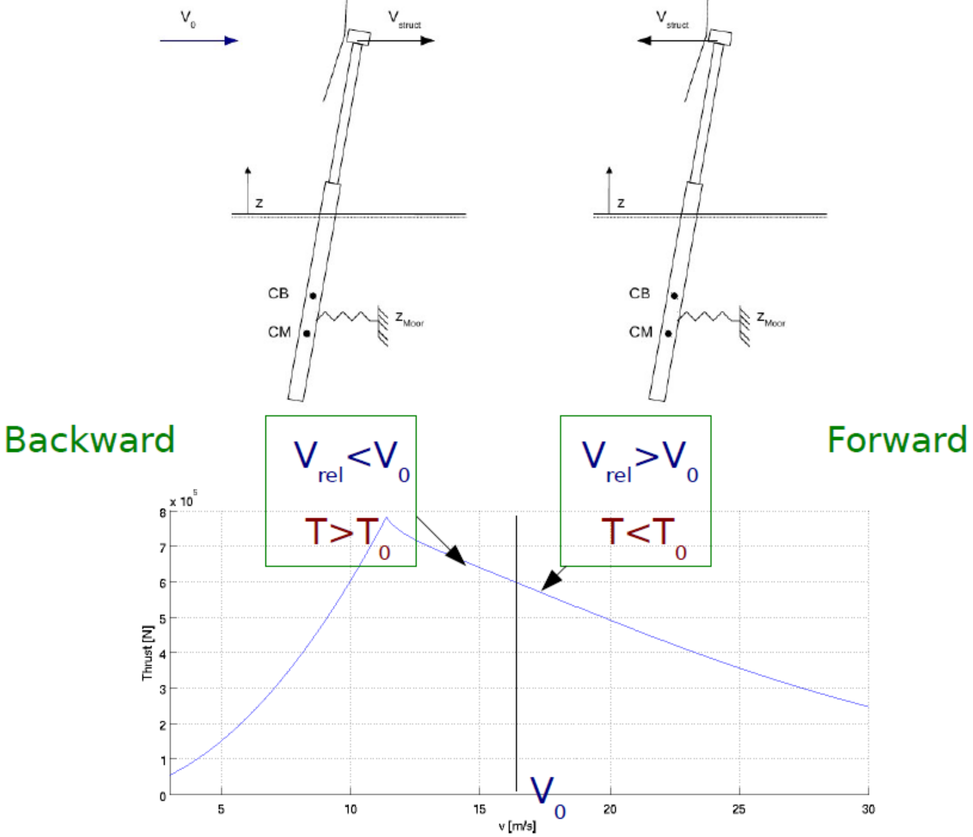
Pitch instability for floating WT



The Science of Making Torque from Wind IOP Publishing
Journal of Physics: Conference Series **75** (2007) 012073 doi:10.1088/1742-6596/75/1/012073

A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine.

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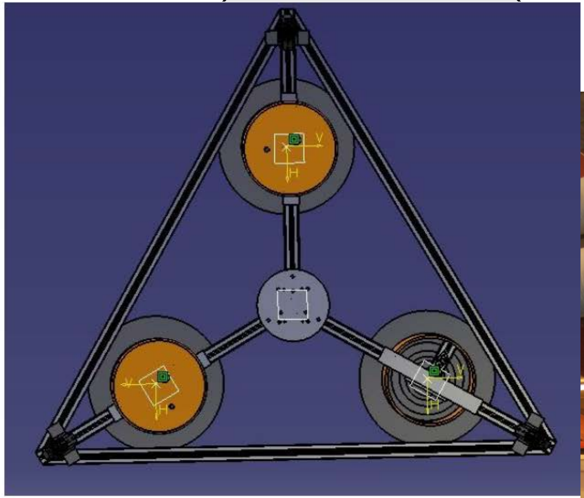
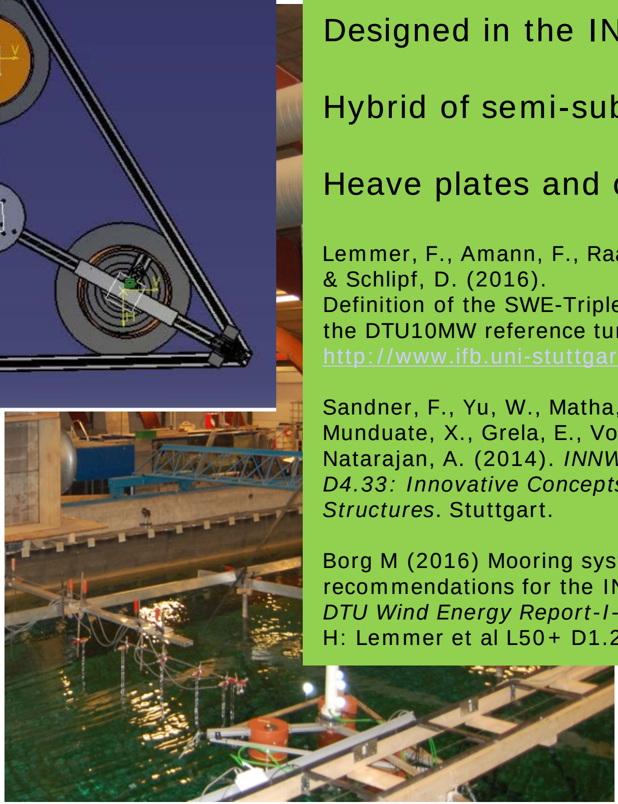
Control, nacelle and rotor ID
Wind climate and waves
Rotor design
Results
The Triple Spar floater
Re-modelling





Designed in the INNWIND.EU project.

Hybrid of semi-sub and spar.

Heave plates and catenary mooring

Lemmer, F., Amann, F., Raach, S., & Schlipf, D. (2016). Definition of the SWE-TripleSpar platform for the DTU10MW reference turbine. http://www.ifb.uni-stuttgart.de/windenergie/downloads

Sandner, F., Yu, W., Matha, D., Azcona, J., Munduate, X., Grela, E., Voutsinas, S., Natarajan, A. (2014). *INNWIND.EU D4.33: Innovative Concepts for Floating Structures*. Stuttgart.

Borg M (2016) Mooring system analysis and recommendations for the INNWIND Triple Spar concept. *DTU Wind Energy Report-I-0448*, Kgs. Lyngby, Denmark.
H: Lemmer et al L50+ D1.2: Simplified models

Dimension	Prototype Scale	Froude Model Scale	Actual Model Scale (incl. instrumentation)
Platform			
Draft	54.5m	908mm	918mm
Elevation of tower base above MSL	25.0m	417mm	333mm
Column diameter	15.0m	250mm	250mm
Column length	65.0m	1083mm	1100mm
Deck elevation above MSL	10.5m	175mm	182mm
Centre offset from tower centerline	26.3m	438mm	430mm
Tripod overall height	15.0m	250mm	-
Heave plate diameter	22.5m	375mm	375mm
Heave plate thickness	0.5m	8.3mm	3mm
Displaced volume	29224m^3	0.1353m^3	0.1357m^3
Platform mass	28229t	130.69kg	129.35kg
Centre of mass below MSL	36.02m	600mm	646mm

Wind climate and waves

The Triple Spar floater

Re-modelling

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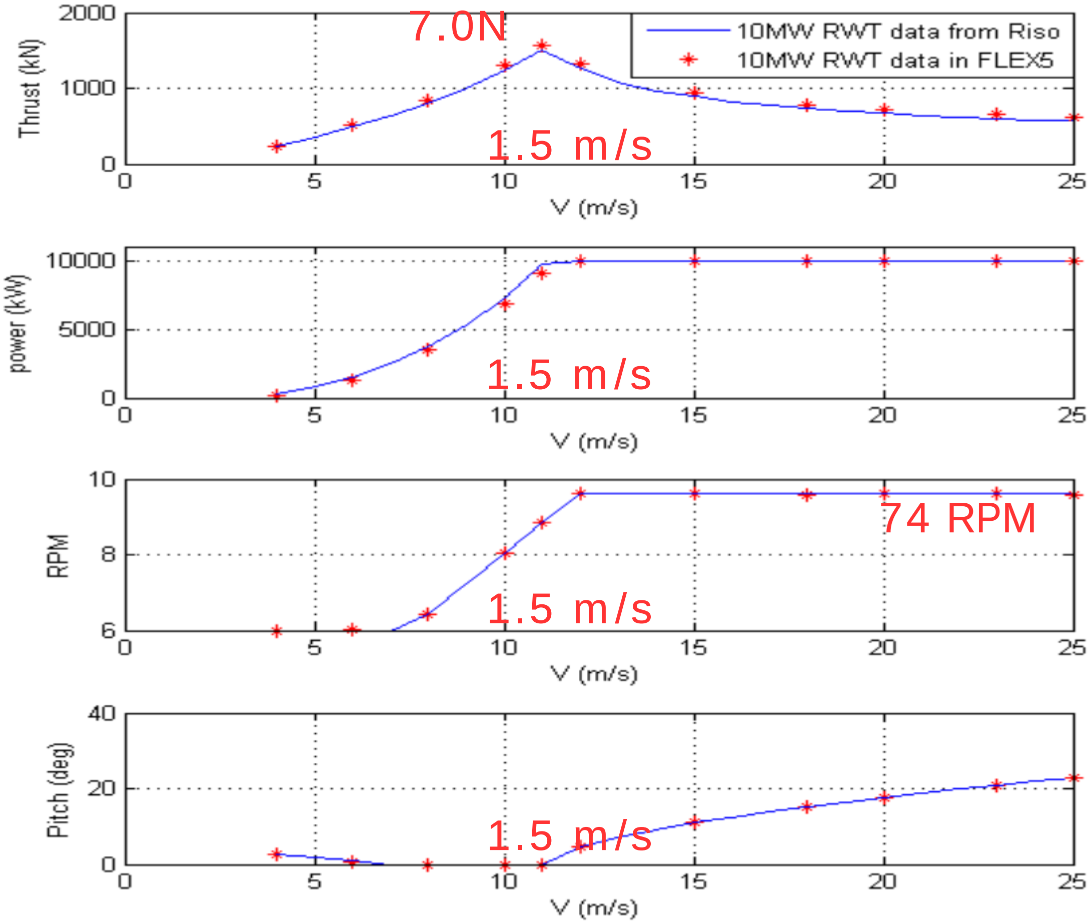
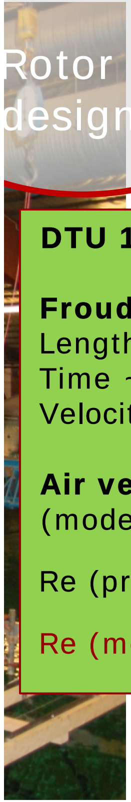
Results

Re-n





Rotor design

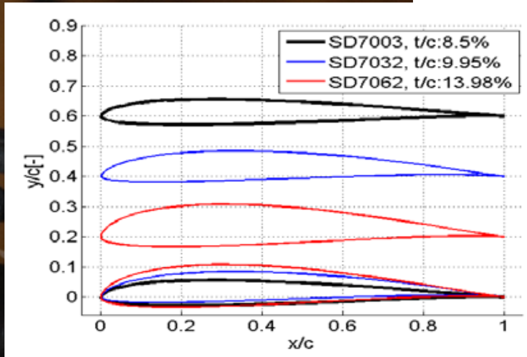
DTU 10MW reference WT

Froude scaling:
Length ~ λ
Time ~ $\lambda^{1/2}$
Velocity ~ $\lambda^{1/2}$

Air velocities
(model scale) ~ 1.5 m/s

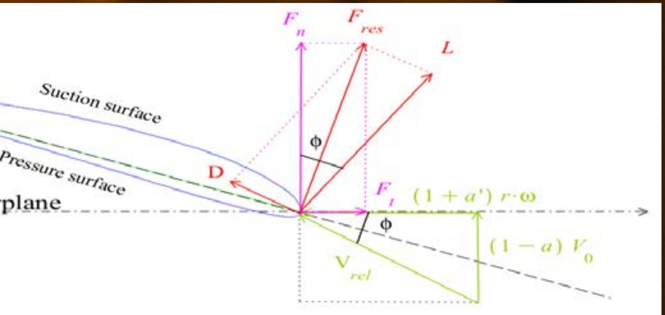
Re (proto scale) ~ 10M

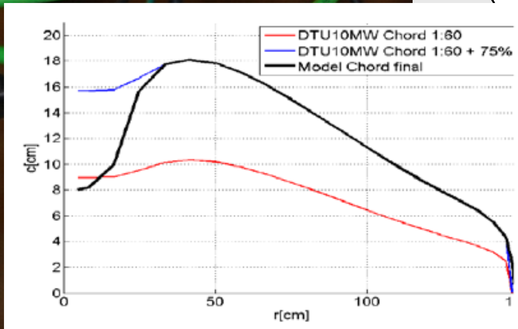
Re (model scale): ~ 25k



Low Re airfoils

75 % increased chord





Wind climate and waves

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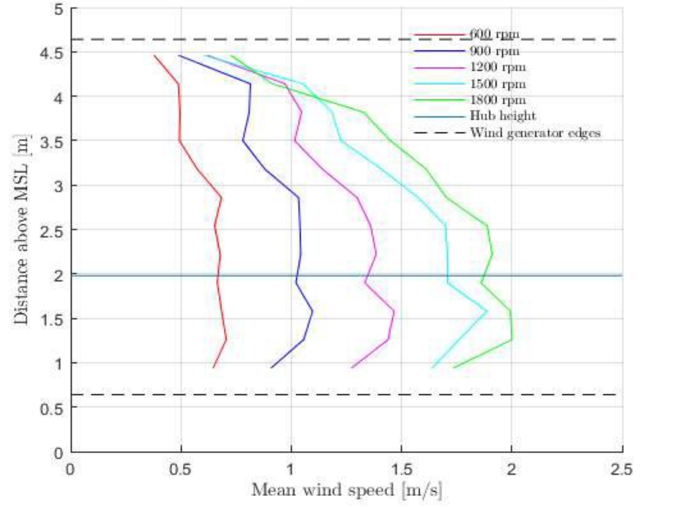

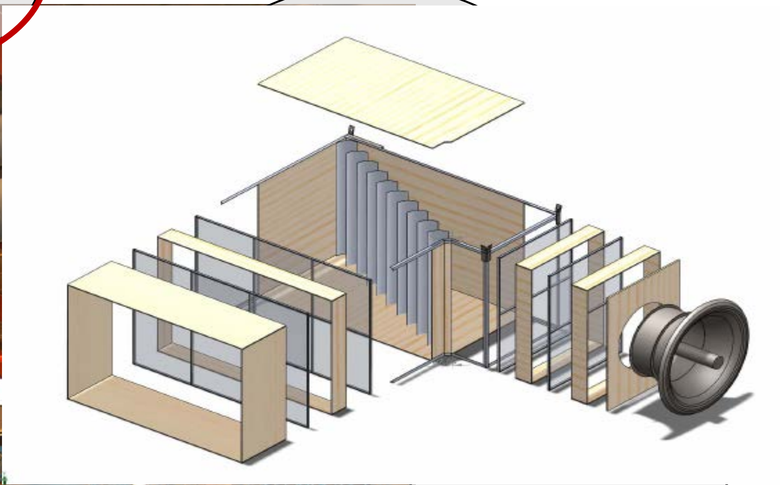

Triple
r floater

SeaState	H [m]	T [s]	W [m/s]
1	0.039	0.71	0.90
2	0.048	0.78	1.00
3	0.055	0.84	1.10
4	0.062	0.89	1.30
5	0.069	0.94	1.50
6	0.08	1.01	1.70
7	0.091	1.08	1.89
8	0.129	1.29	1.89
9	0.159	1.43	1.89
10	0.20	1.60	1.89

6 units

New fan-motors

Wind speed up to 2.1 m/s

Unwanted ‘reverse’ shear

Now fixed !

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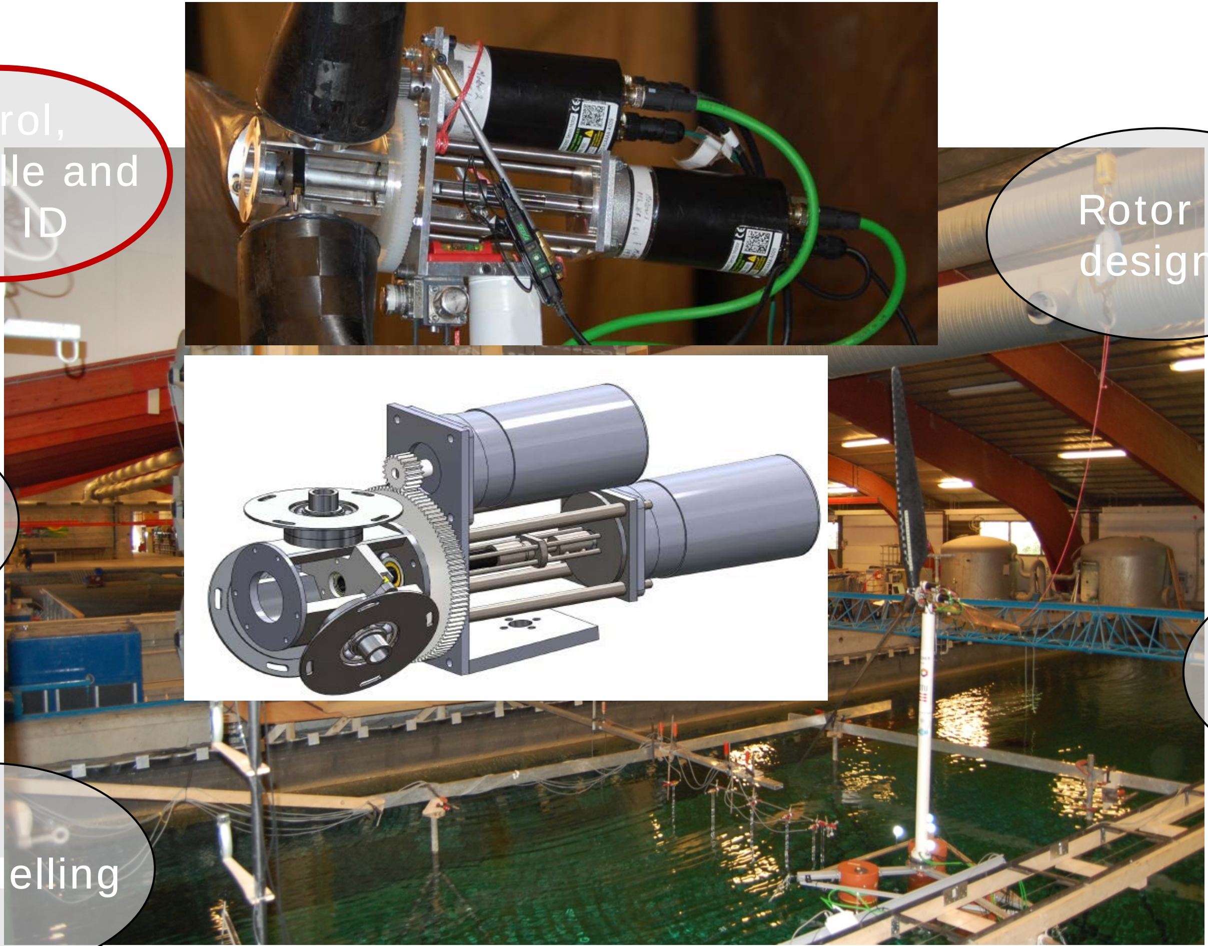
Control, nacelle and rotor ID

Rotor design

Results



The Triple Spar floater

Re-modelling

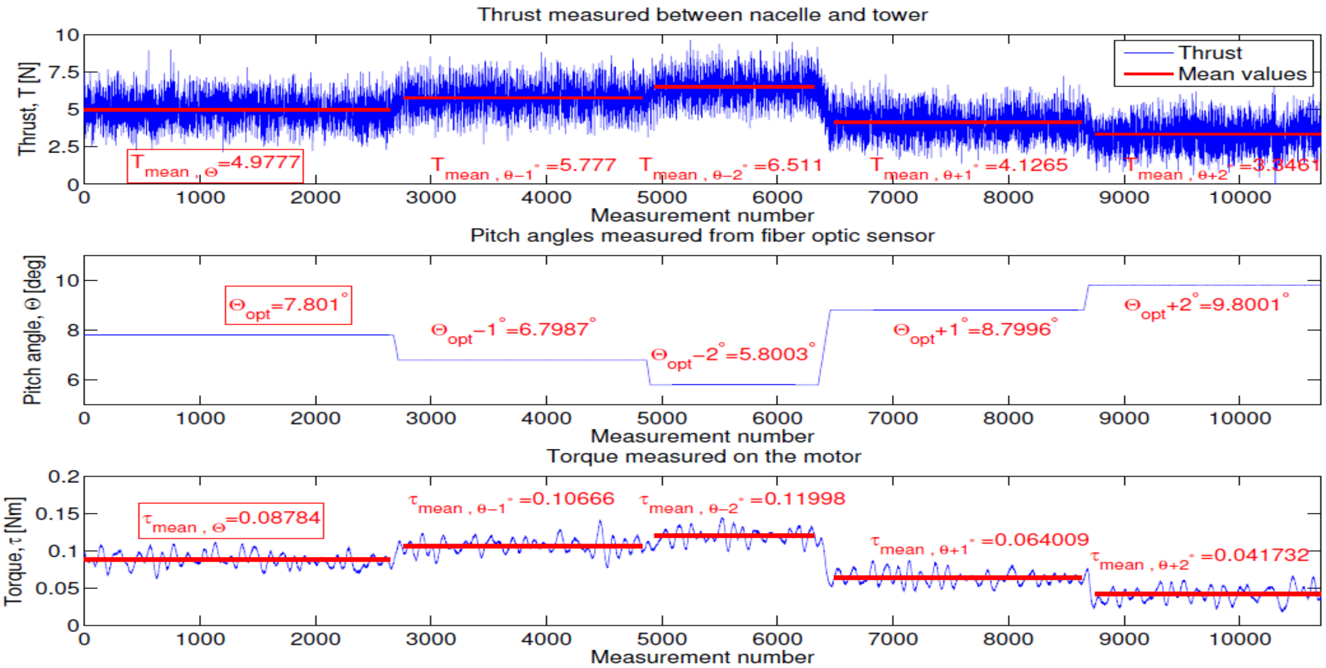
Control, nacelle and

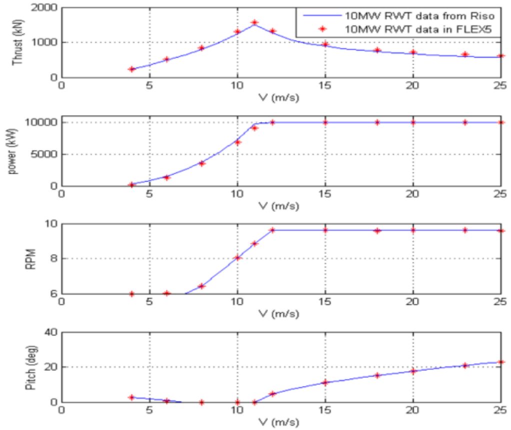
Rotor ID

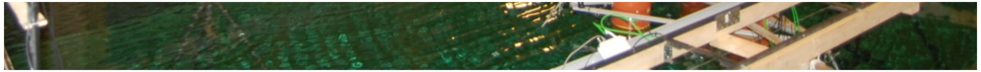
Wind speed -> rotor speed

Measure thrust and torque vs blade pitch

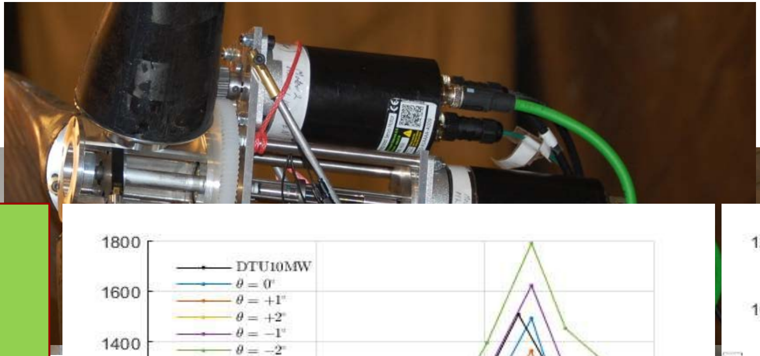
Gives desired blade pitch







Control, nacelle and

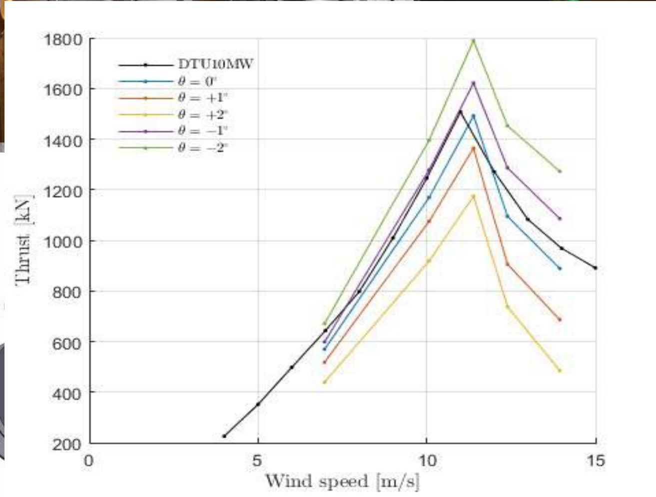


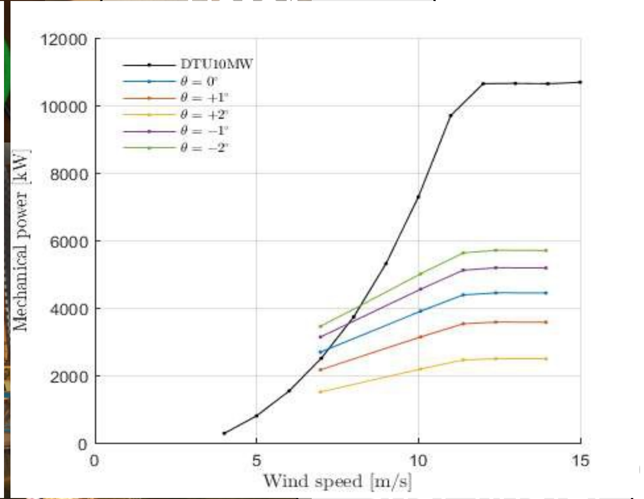
Rotor ID

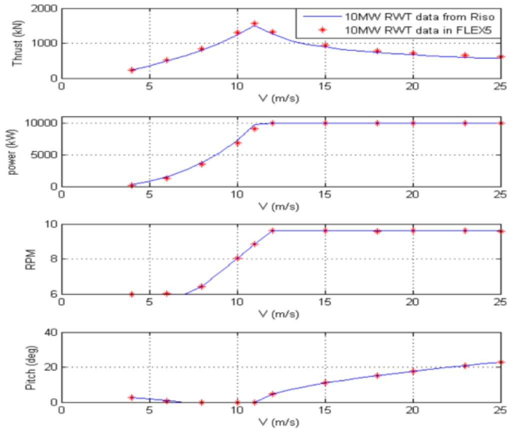
Wind speed -> rotor speed

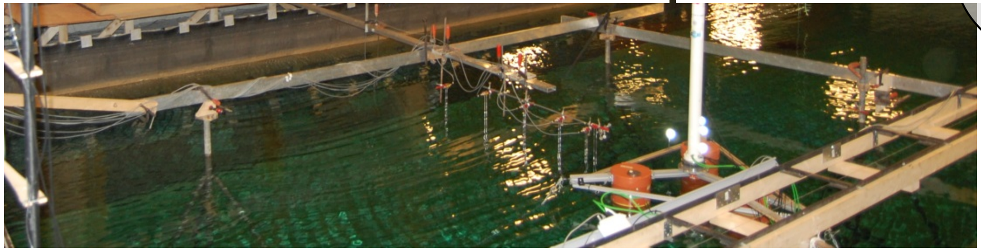
Measure thrust and torque vs blade pitch

Gives desired blade pitch









Spar floater

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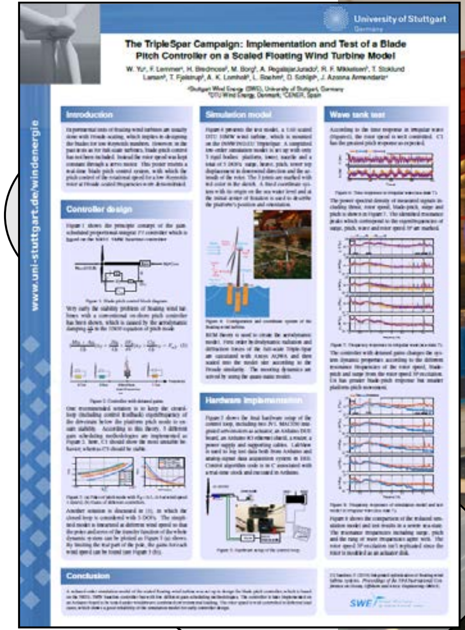
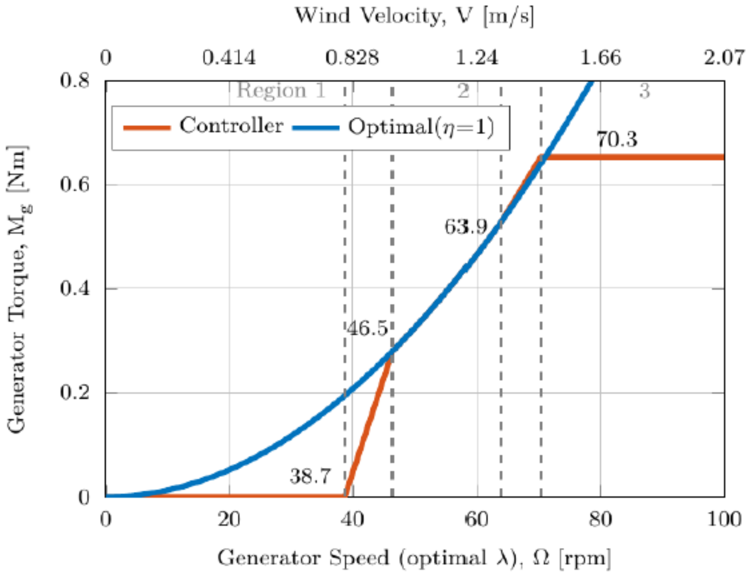
Control, nacelle and rotor ID



SWE Model-in-The-Loop ➡ Torque controller



$M_g(\Omega)=K\Omega^2$

$$\frac{\eta \cdot \rho \cdot A \cdot C_{P,opt} \cdot R^3 \cdot \Omega^2}{2 \cdot \lambda^3_{opt}}$$

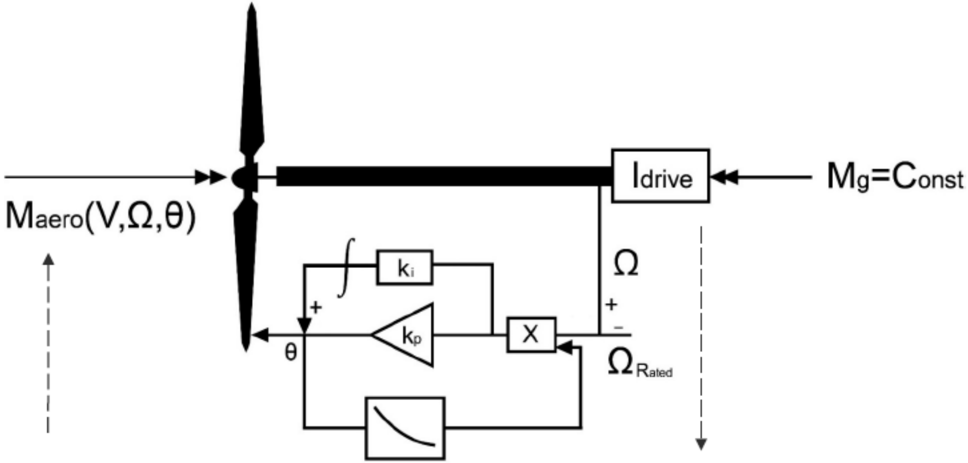
Optimal Cp tracking

$$\frac{\rho \cdot A \cdot C_P \cdot R^3 \cdot \Omega^2}{2 \cdot \lambda^3} \xrightarrow{\eta} \frac{\eta \cdot \rho \cdot A \cdot C_P \cdot R^3 \cdot \Omega^2}{2 \cdot \lambda^3}$$

[Yu Wei, SWE]

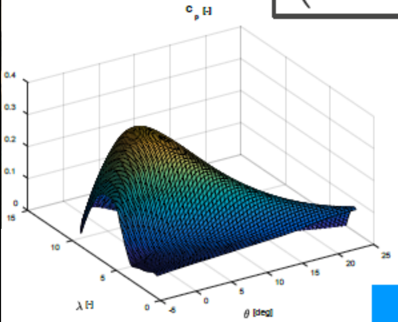
Regulate motor torque to get optimal Cp

SWE Model-in-The-Loop ➡ Pitch controller (1/3)



$$\left(\frac{\partial M_{aero}}{\partial \theta}\right)\Delta\theta \leftarrow \Delta\theta = K_p \Delta\Omega + K_i \int_0^t \Delta\Omega\, dt \leftarrow I_{Drive}\Delta\Omega \qquad \Omega = \dot{\varphi}$$

$$I_{Drive}\ddot{\varphi} + \left(-\frac{\partial M_{aero}}{\partial \theta}\right) K_P\, \dot{\varphi} + \left(-\frac{\partial M_{aero}}{\partial \theta}\right) K_I\, \varphi = 0$$



Pitch sensitivity varies

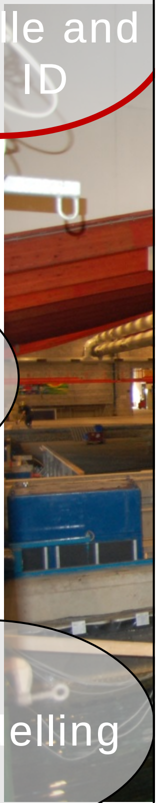
[Yu Wei, SWE]

Regulate blade pitch to get constant rotational speed

Control, nacelle and rotor ID

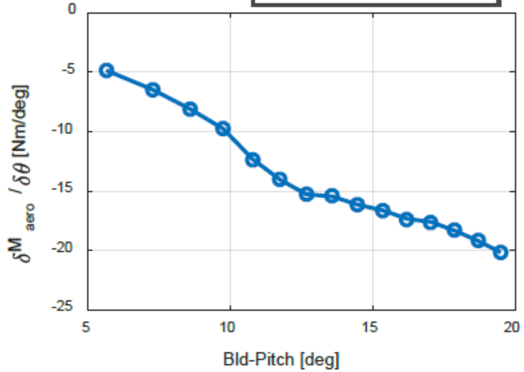
Results

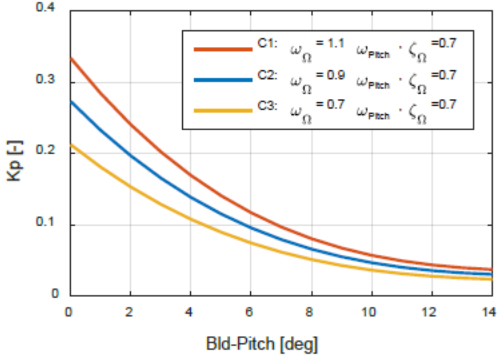
Re-modelling

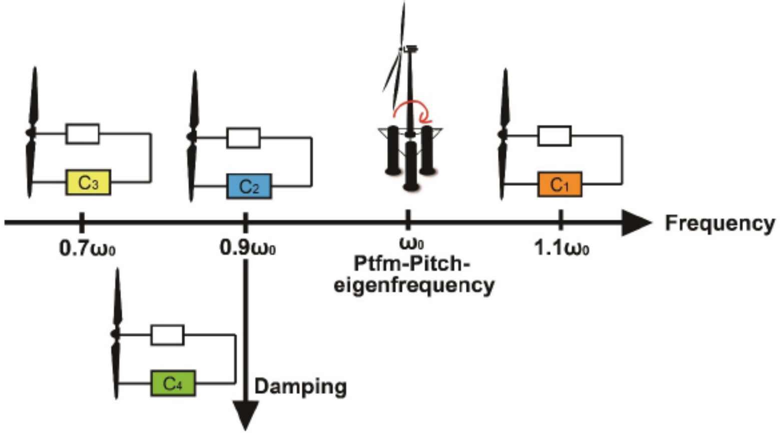


SWE Model-in-The-Loop ➡ Pitch controller (2/3)

Pitch sensitivity → Gain scheduling







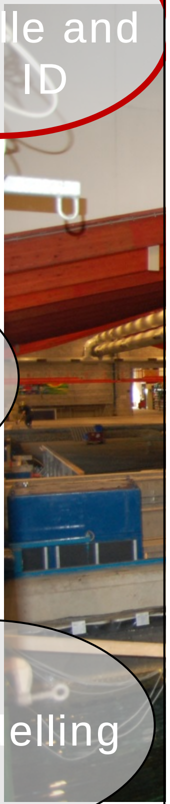
How does the eigenfrequency of the drivetrain closed-loop affect the system dynamic?

[Yu Wei, SWE]

Control, nacelle and rotor ID

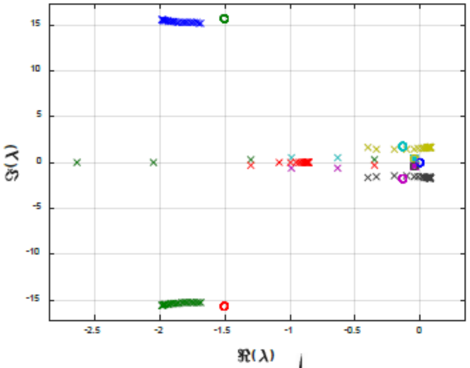
Results

Re-modelling

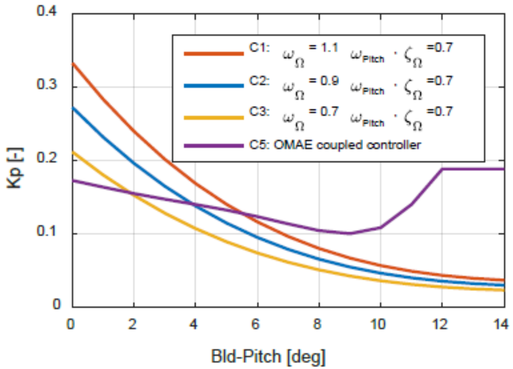


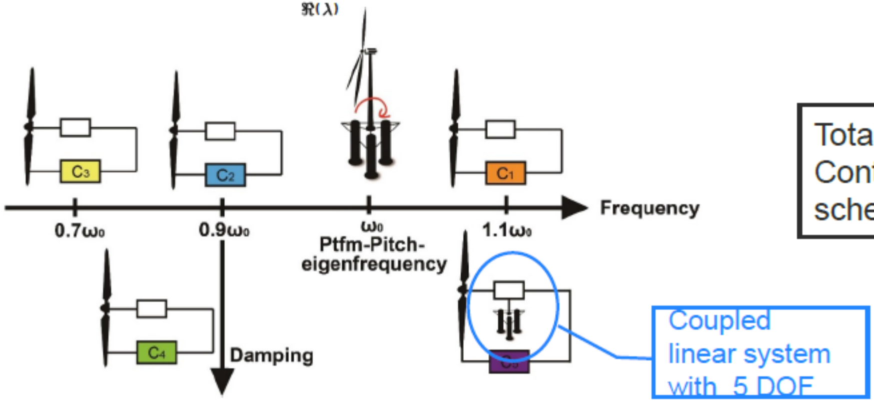
SWE Model-in-The-Loop ➡ Pitch controller (3/3)

Pole-zero map of the complete linear closed-loop system



Gain scheduling





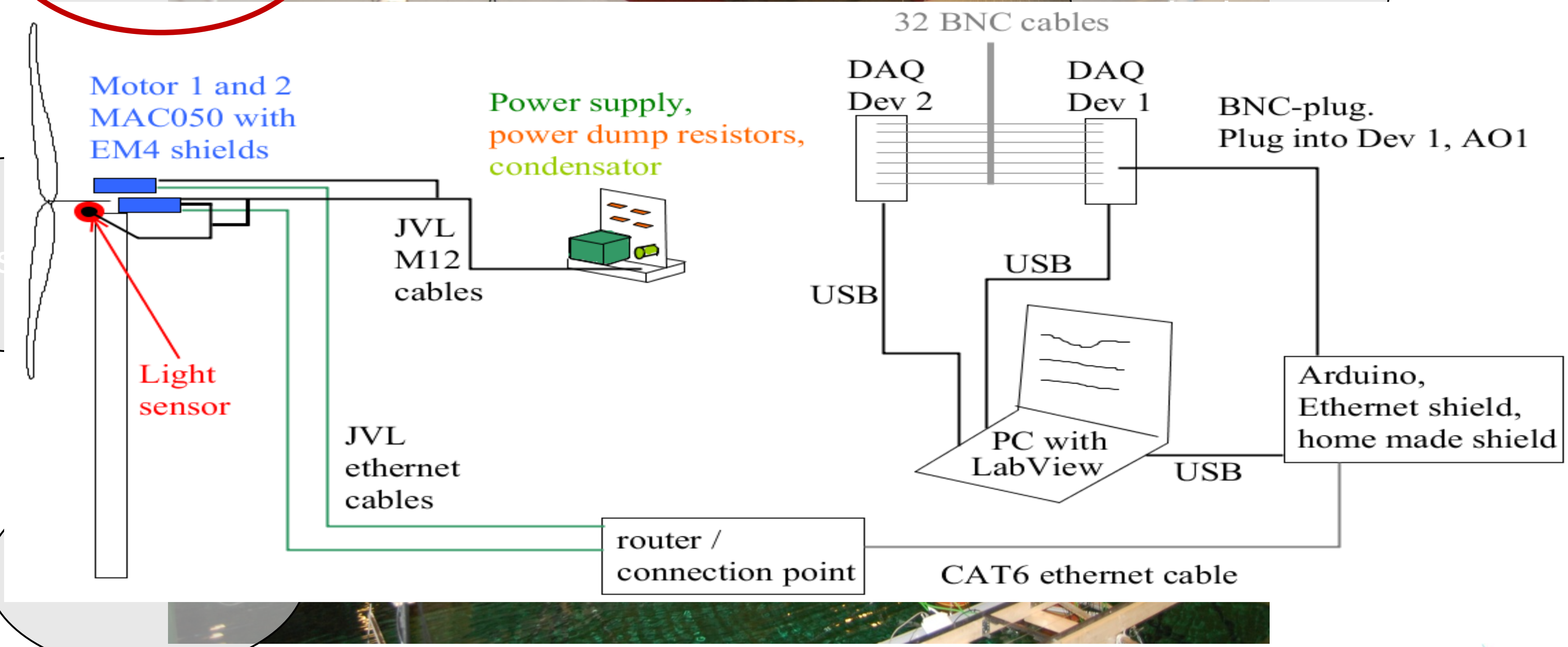
Totally 5 Blade-Pitch PI Controller with different gain scheduling to be tested.

[Yu Wei, SWE]

Control, nacelle and rotor ID

Wind climate and waves

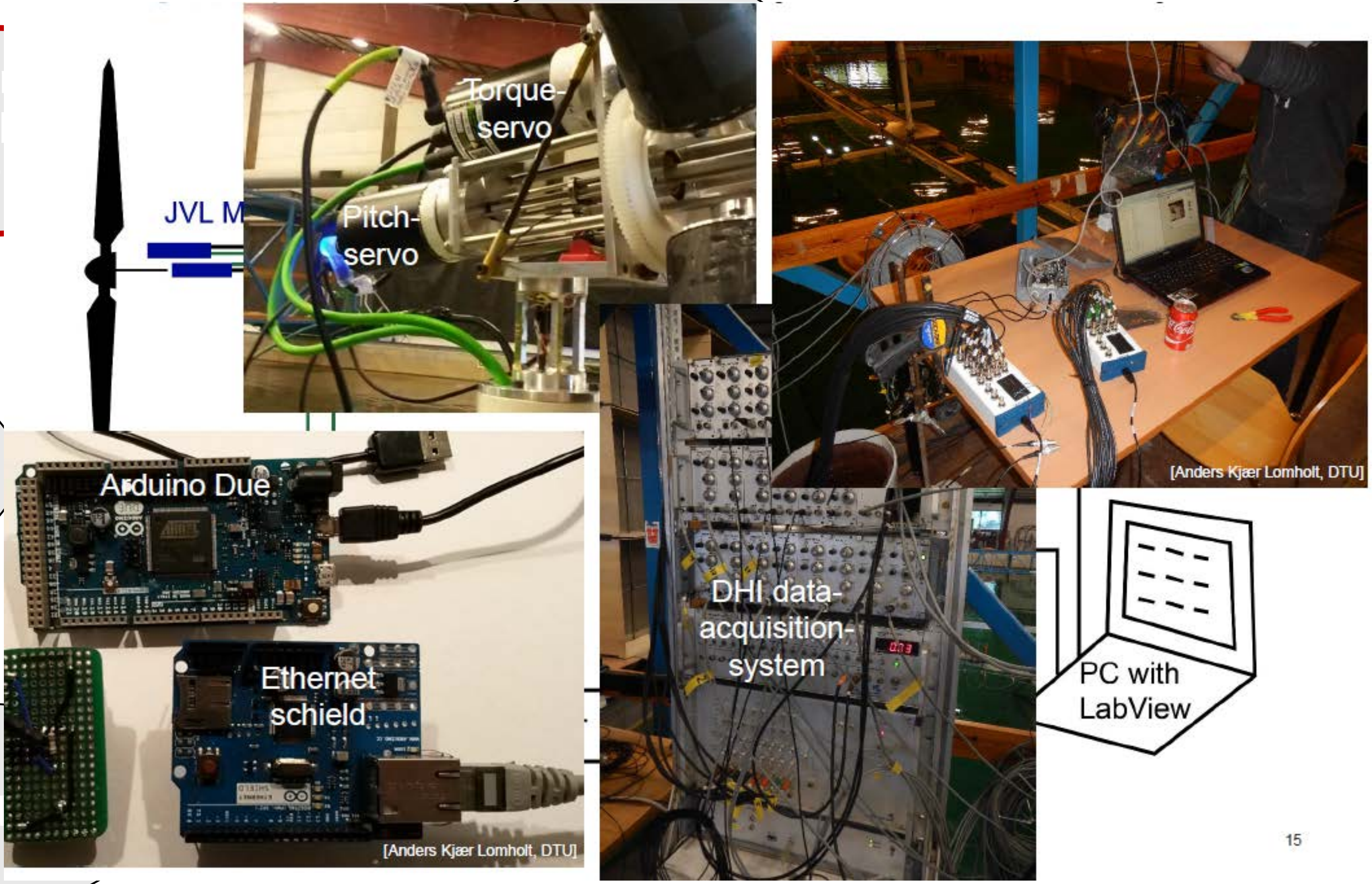
Rotor



Cont
nacel
rotor

Results

Re-mod



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Control, nacelle and rotor ID

Wind climate and waves

Rotor design

Results

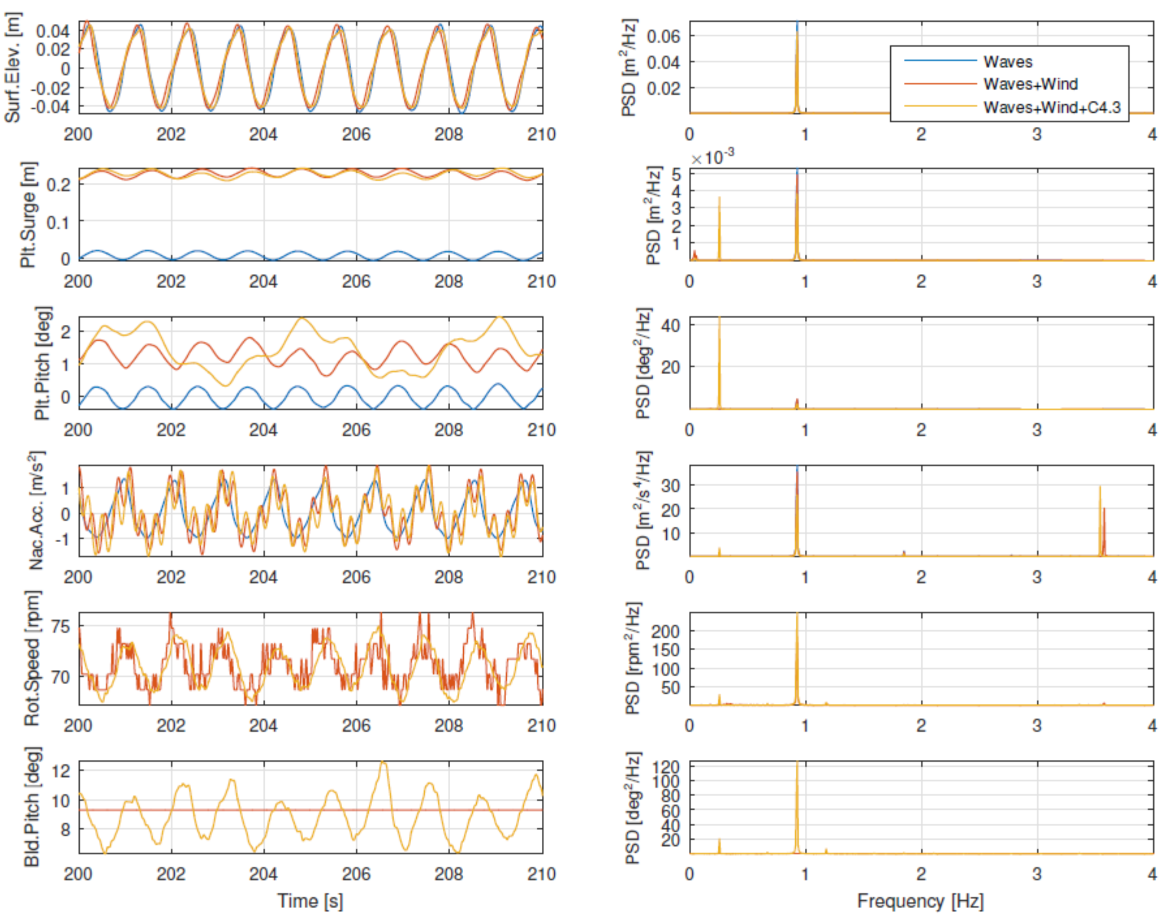
The Triple Spar floater

Re-modelling

Regular waves

Results

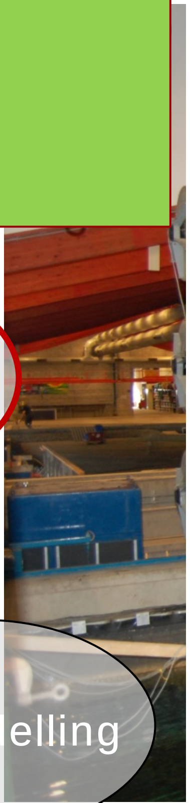
Re-modelling

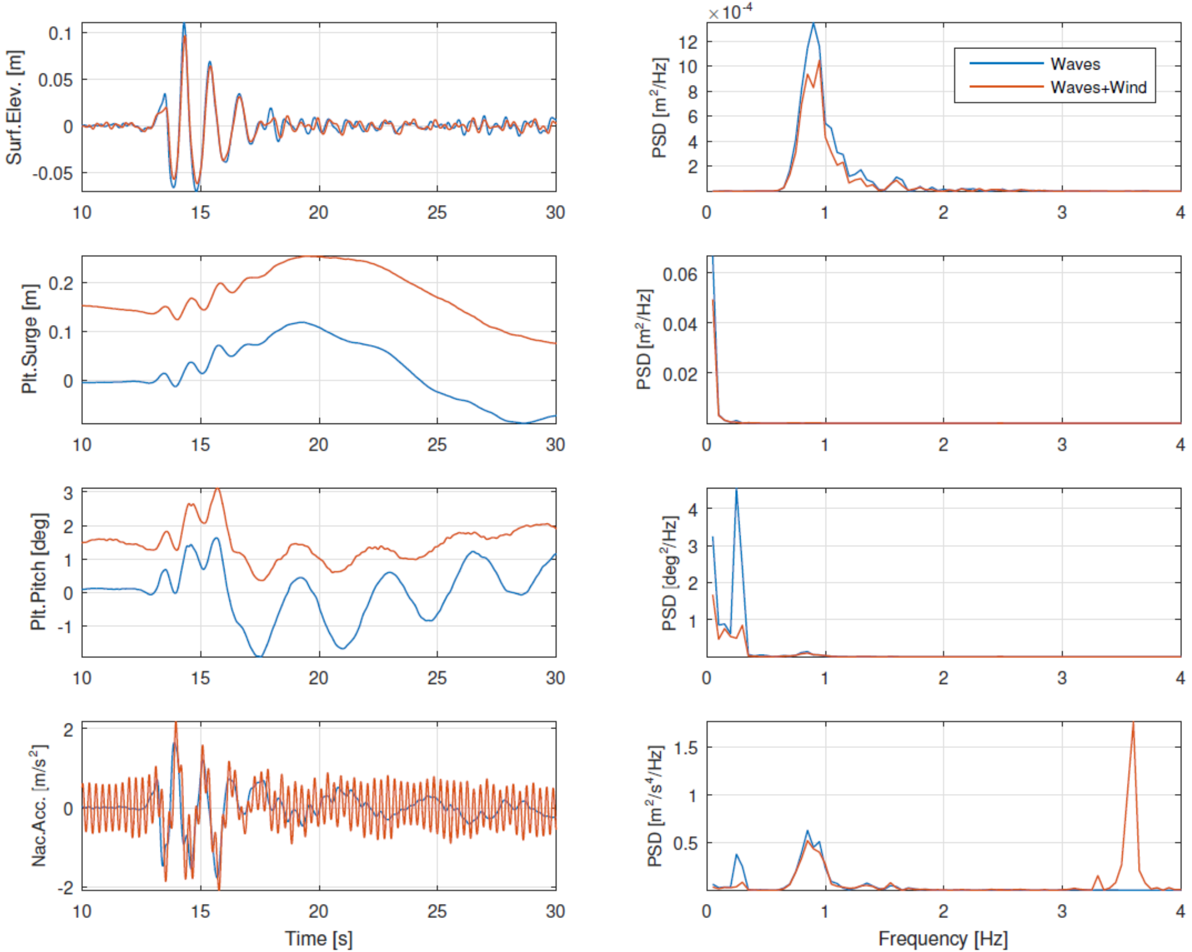


Focused wave

Results

Re-modelling





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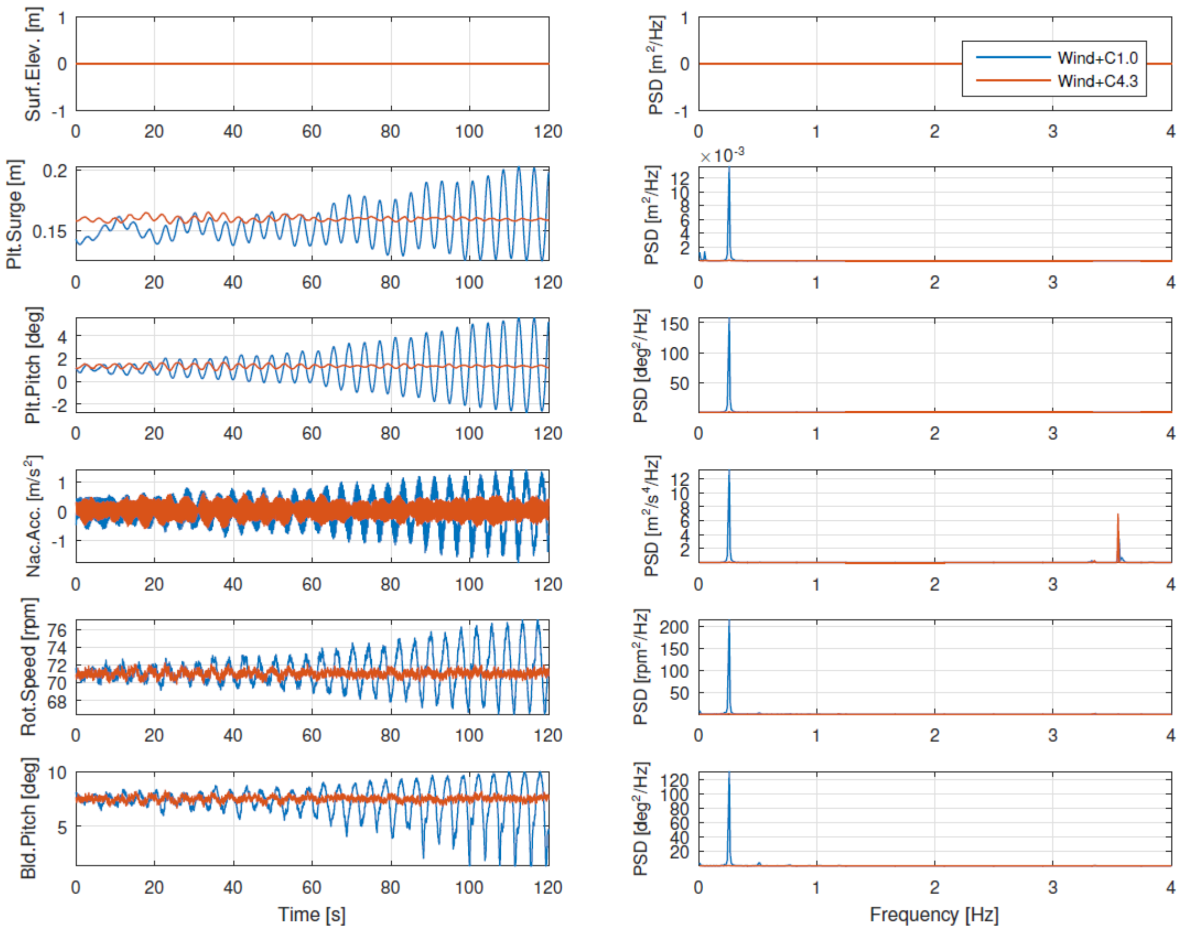
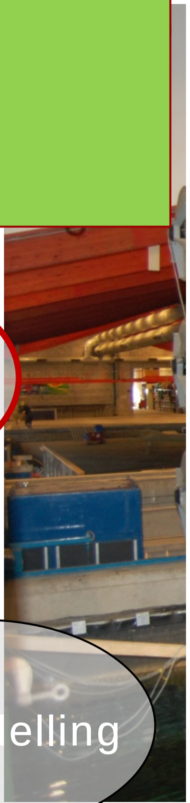
Platform pitch instability

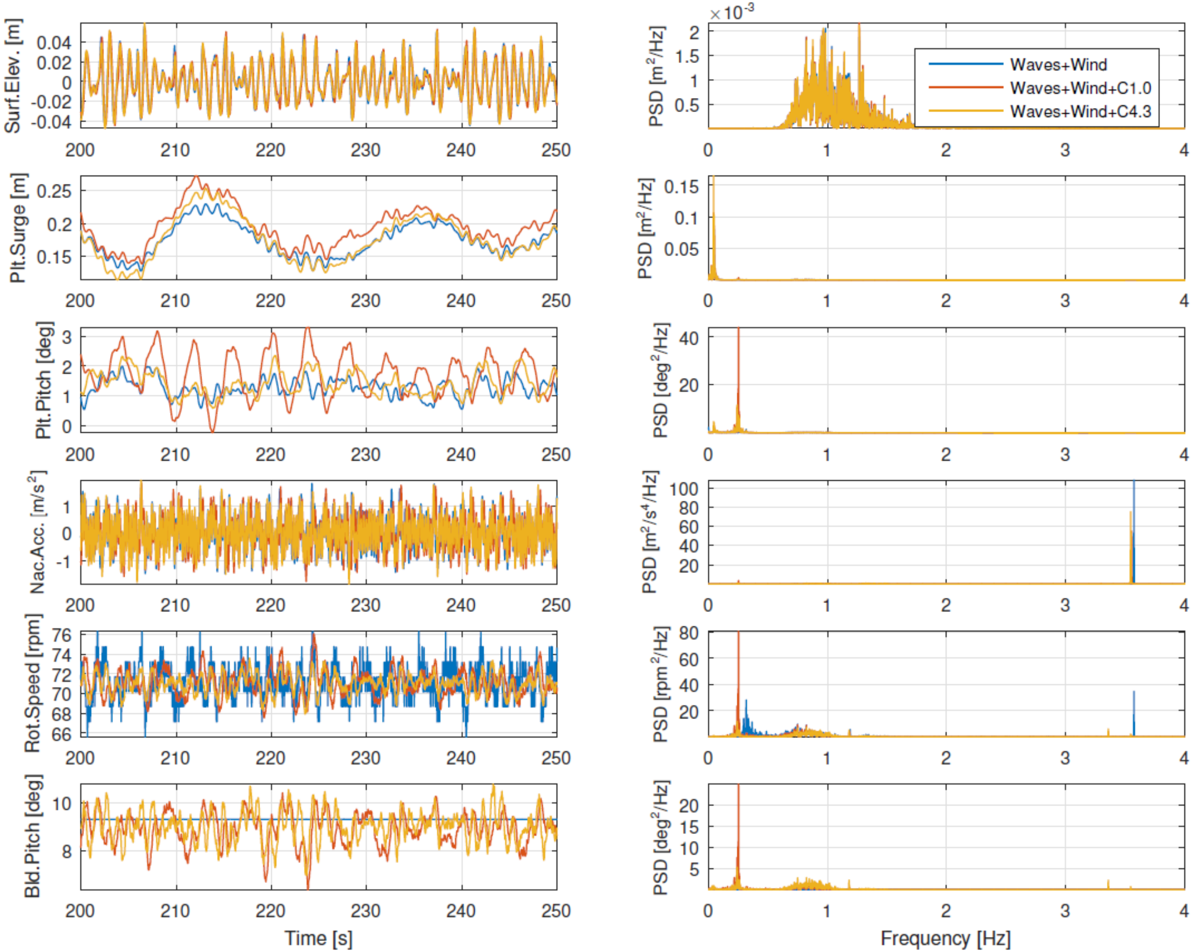
Results

Re-modelling



Irregular waves





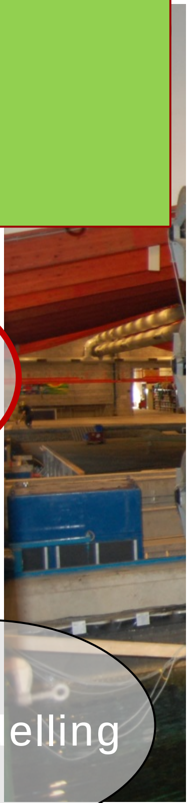
Results

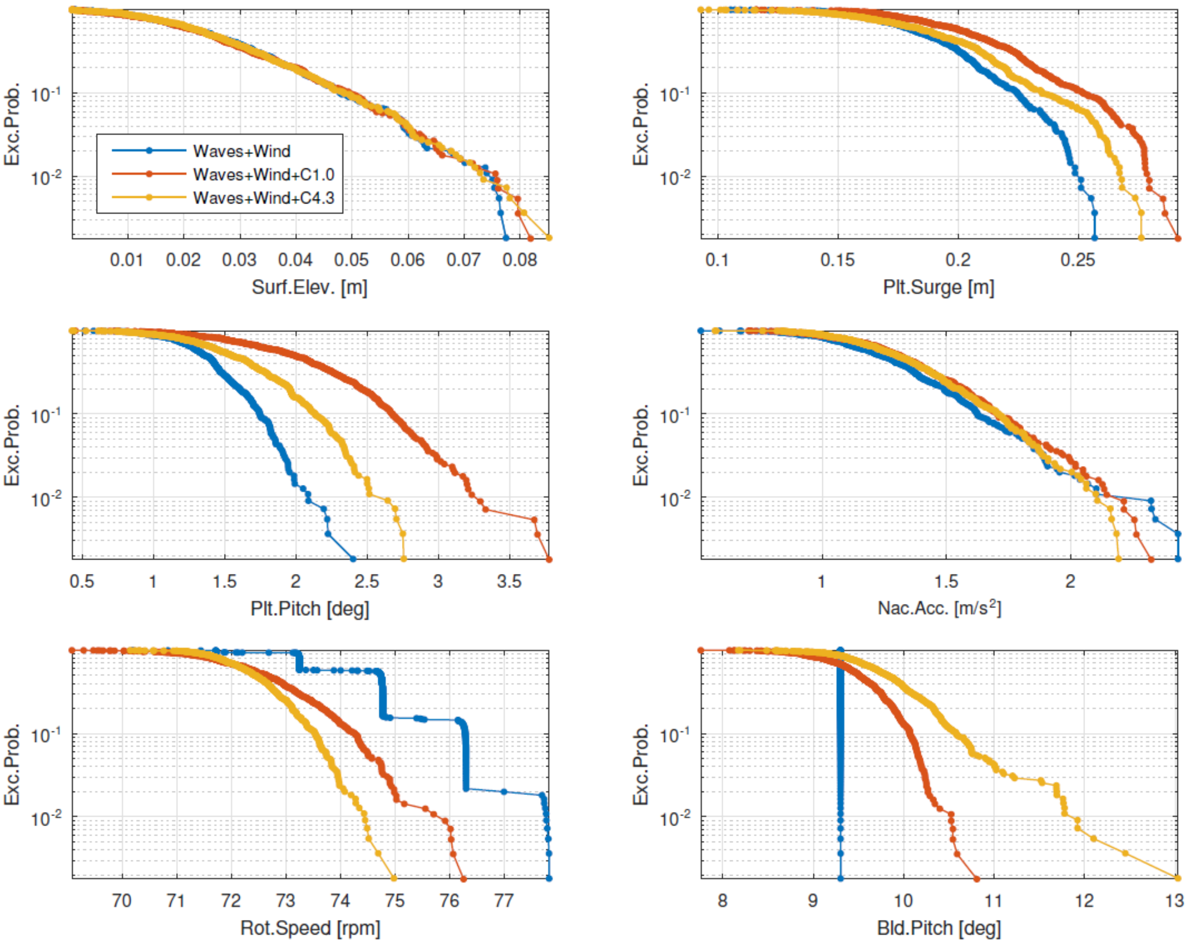
Re-modelling

Irregular waves

Results

Re-modelling



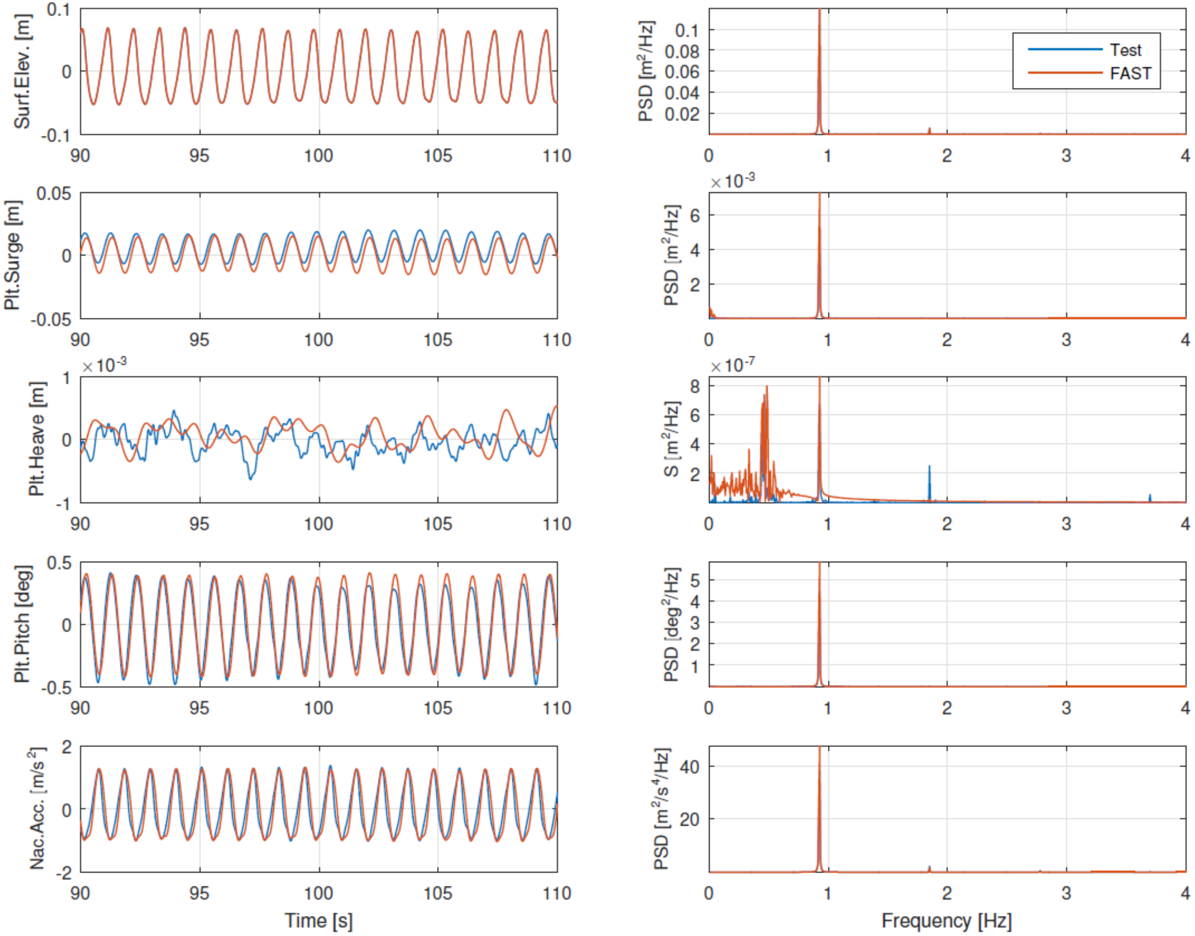


Control, nacelle and rotor ID

Re-modelling in FAST

Regular wave-only case

Re-modelling



Control, nacelle and rotor ID

Wind climate and waves

Rotor design

Results

The Triple Spar floater

Re-modelling