

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



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DTU Wind Energy  
University of Stuttgart  
CENER

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



## The Triple Spar Campaign: Implementation and Test of a Blade Pitch Controller on a Scaled Floating Wind Turbine Model

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[www.uni-stuttgart.de/windenergie](http://www.uni-stuttgart.de/windenergie)

### Introduction

Experimental tests of floating wind turbines are usually done with Frondt scaling, which implies re-designing the blades for low Reynolds numbers. However, in the past tests as for full-scale turbines, blade-pitch control has not been included. Instead the rotor speed was kept constant through a servo motor. This poster presents a complete blade pitch control system, which matches the pitch control of the rotational speed for a low Reynolds number at the pre-scaled frequencies as demonstrated.

### Controller design

Figure 1 shows the principle concept of the gain-scheduled proportional-integral PI controller which is based on the NREL SWM baseline controller

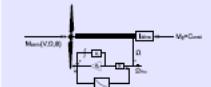
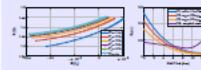


Figure 1: Blade-pitch control block diagram.  
Very early the stability problem of floating wind turbines with a conventional on-shore pitch controller has been shown, which is caused by the aerodynamic damping  $\frac{dF}{d\theta}$  in the 1DOF equation of pitch mode

$$\frac{M\ddot{\theta} + A\dot{\theta}}{L_f} + \frac{B\theta}{L_f} + \frac{dF}{d\theta}\dot{\theta}^2 + \frac{C_{\theta\theta}}{L_f}\theta^2 = F_{ext}, \quad (1)$$

One recommended solution is to keep the closed-loop (including controller block) eigenvalues of the floating wind platform away from the eigenvalues of the system. According to this theory, 3 different gain scheduling methodologies are implemented as Figure 2. Here, C3 should show the most unstable behavior, whereas C3 should be stable.



Another solution is discussed in [1], in which the closed-loop is consistent with 5 DOFs. The simplified model is linearized at different wind speed so that the poles and zeros of the transfer function of the whole dynamic system can be plotted as Figure 3 (a) shows. By limiting the real part of the pole, the gains for each wind speed can be found (see Figure 3 (b)).

### Simulation model

Figure 4 presents the test model, a 1:20 scaled DTU 10MW wind turbine, which is mounted on the INNWIND.EU TripleSpar. A simplified 10-DOF simulation model is set up with only 3 rigid bodies: platform, tower, nacelle and a total of 5 masses: surge, heave, pitch, tower top displacement and a damping element between the tower and the nacelle. The 3 joints are marked with red color in the sketch. A fixed coordinate system with its origin on the sea water level and at the initial center of rotation is used to describe the platform's position and orientation.



Figure 4: Configuration and coordinate system of the floating wind turbine.

BEM theory is used to create the aerodynamic model. First order by hydrodynamic radiation and diffraction forces are calculated. The loads are calculated with Amanzi AGWA and then scaled into the model size according to the Frondt similarity. The mooring dynamics are solved by using the quasi-static model.

### Hardware implementation

Figure 5 shows the final hardware setup of the control loop, including two PVL-MAC010 integrated controllers, an Arduino Uno R3 board, an Arduino R3 ethernet shield, a laptop, a power supply and supporting cables. LabVIEW is used to log test data both from Arduino and analog-signal data acquisition system in DHL. Control algorithm code is in C associated with a real-time clock and executed in Arduino.

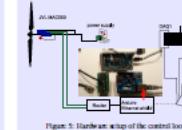


Figure 6 shows the comparison of the reduced simulation model and test results in a severe sea state. The resonance frequencies including surge, pitch and the range of wave frequencies agree well. The rotor speed 3P excitation isn't replicated since the rotor is modeled as an actuator disk.

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DTU Wind Energy  
University of Stuttgart  
CENER

DTU Wind Energy  
Department of Wind Energy



# 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)



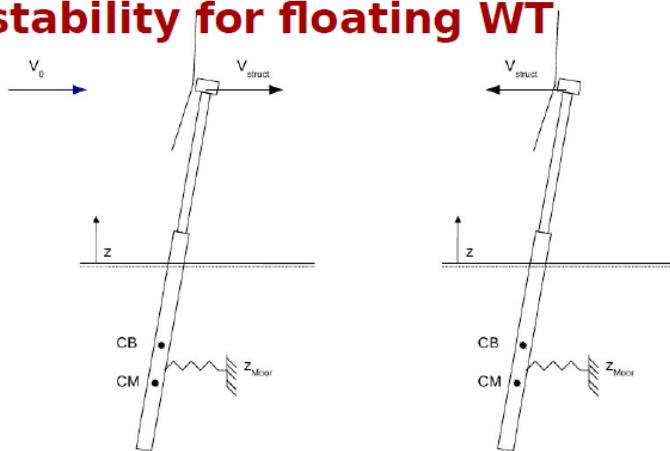
Sandner et al (2015)



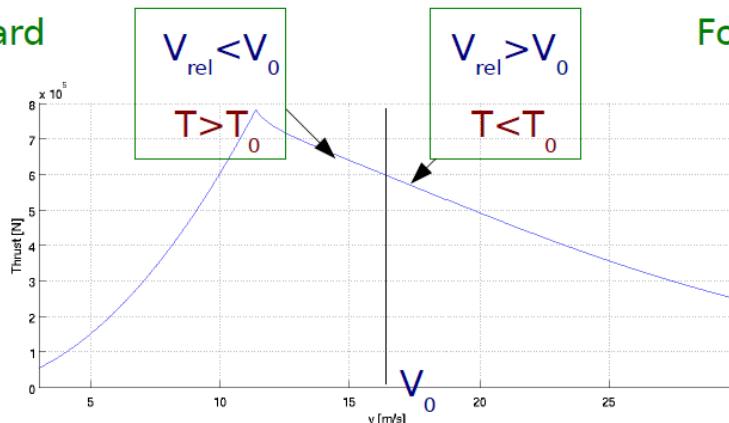
Bredmose et al (2015)  
Pegalajar-Jurado et al (2016)



# Pitch instability for floating WT



Backward



Forward

The Science of Making Torque from Wind  
Journal of Physics: Conference Series 75 (2007) 012073

IOP Publishing  
doi:10.1088/1742-6596/75/1/012073

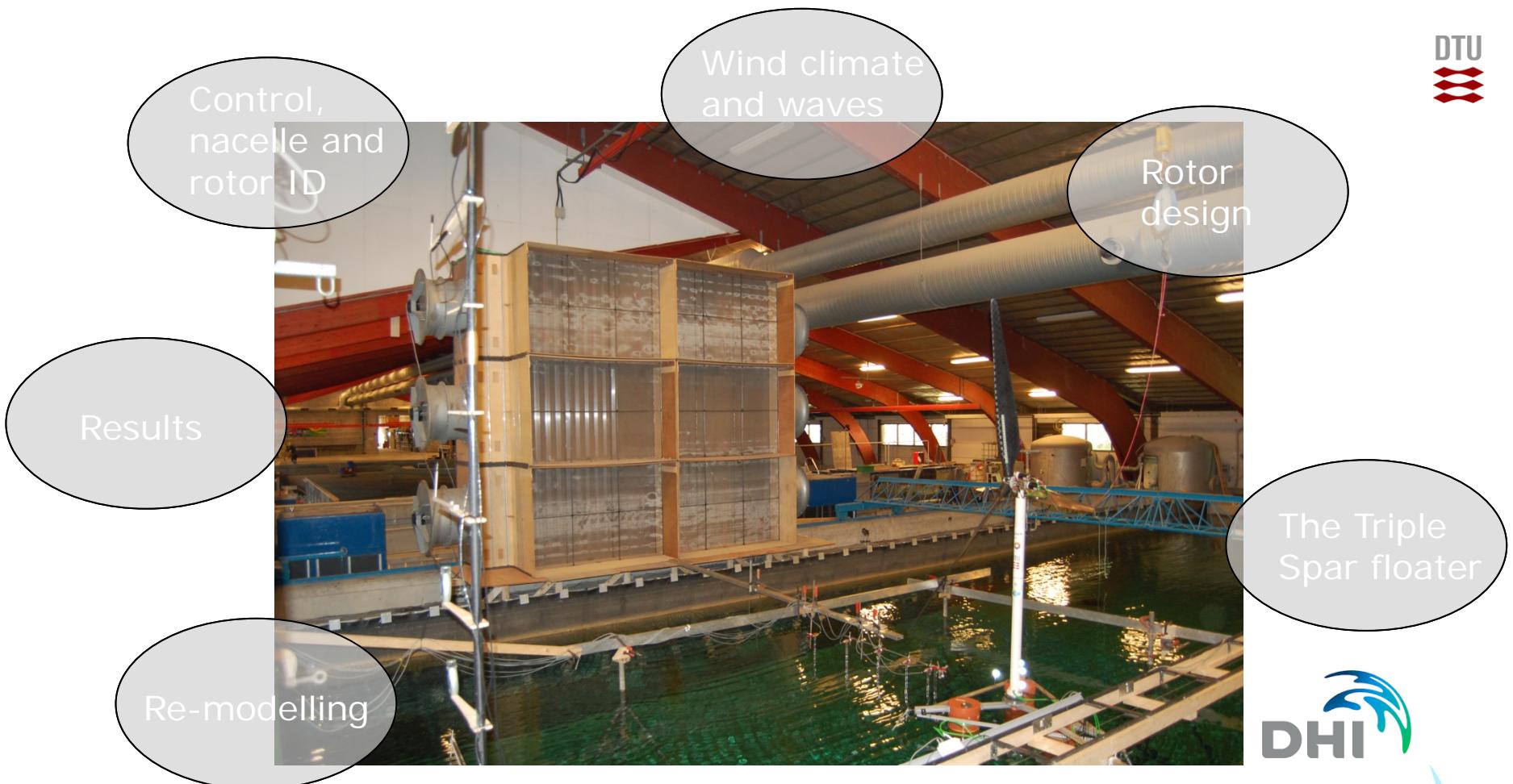
A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine.

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<sup>1</sup> Wind Energy Department, Risøe National Laboratory – Technical university of Denmark, P.O. Box 49, DK - 4000 Roskilde, Denmark

<sup>2</sup> Hydro Oil & Energy, P.O. Box 7190, N – 5020 Bergen, Norway

Corresponding author: torben.juul.larsen@risoe.dk



Designed in the INNWIND.EU project.

Hybrid of semi-sub and spar.

Heave plates and catenary mooring

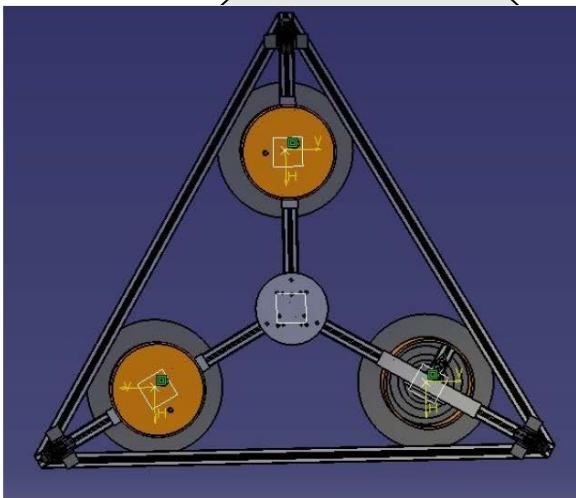
Lemmer, F., Amann, F., Raach, S., & Schlipf, D. (2016).

Definition of the SWE-TripleSpar platform for the DTU10MW reference turbine.

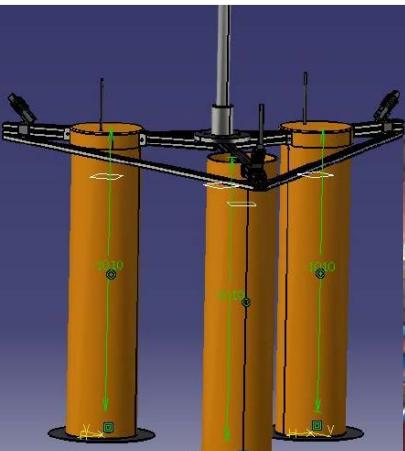
<http://www.ifb.uni-stuttgart.de/windenergie/downloads>

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.

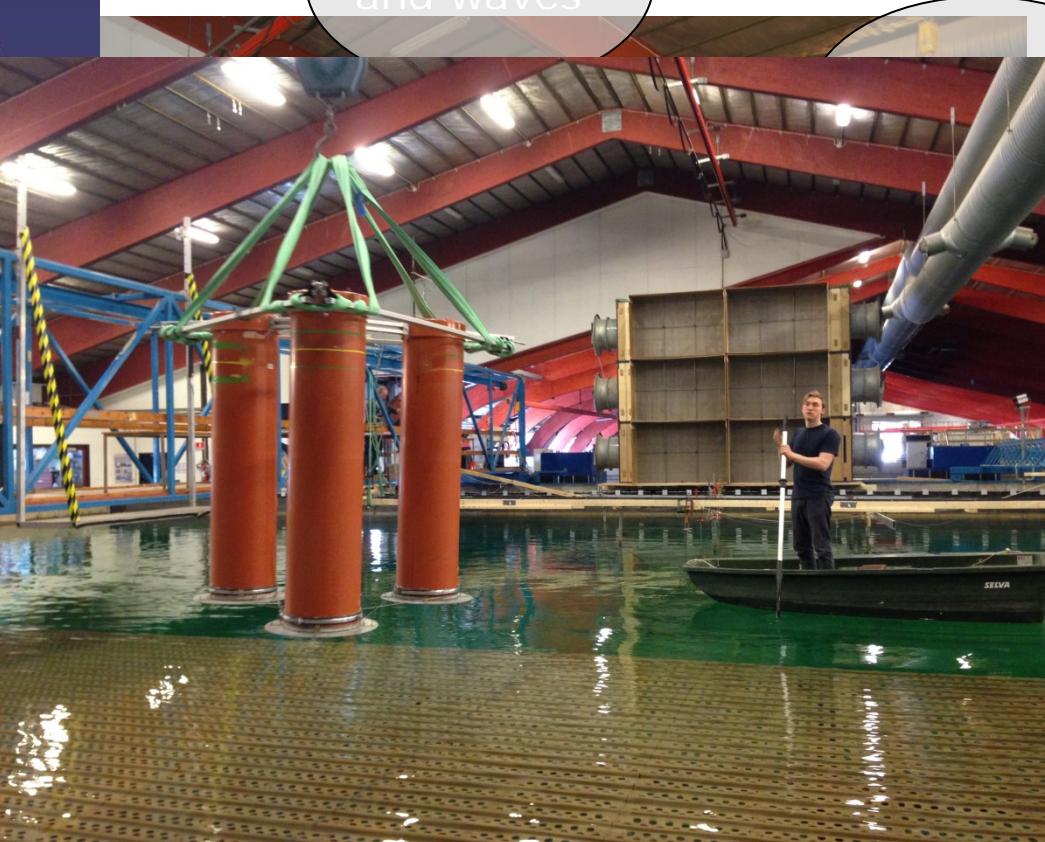
Borg M (2016) Mooring system analysis and recommendations for the INNWIND Triple Spar concept. *DTU Wind Energy Report-I-0448*, Kgs. Lyngby, Denmark.  
H: Lemmer et al L50+ D1.2: Simplified models



Wind climate  
and waves



Re-modelling

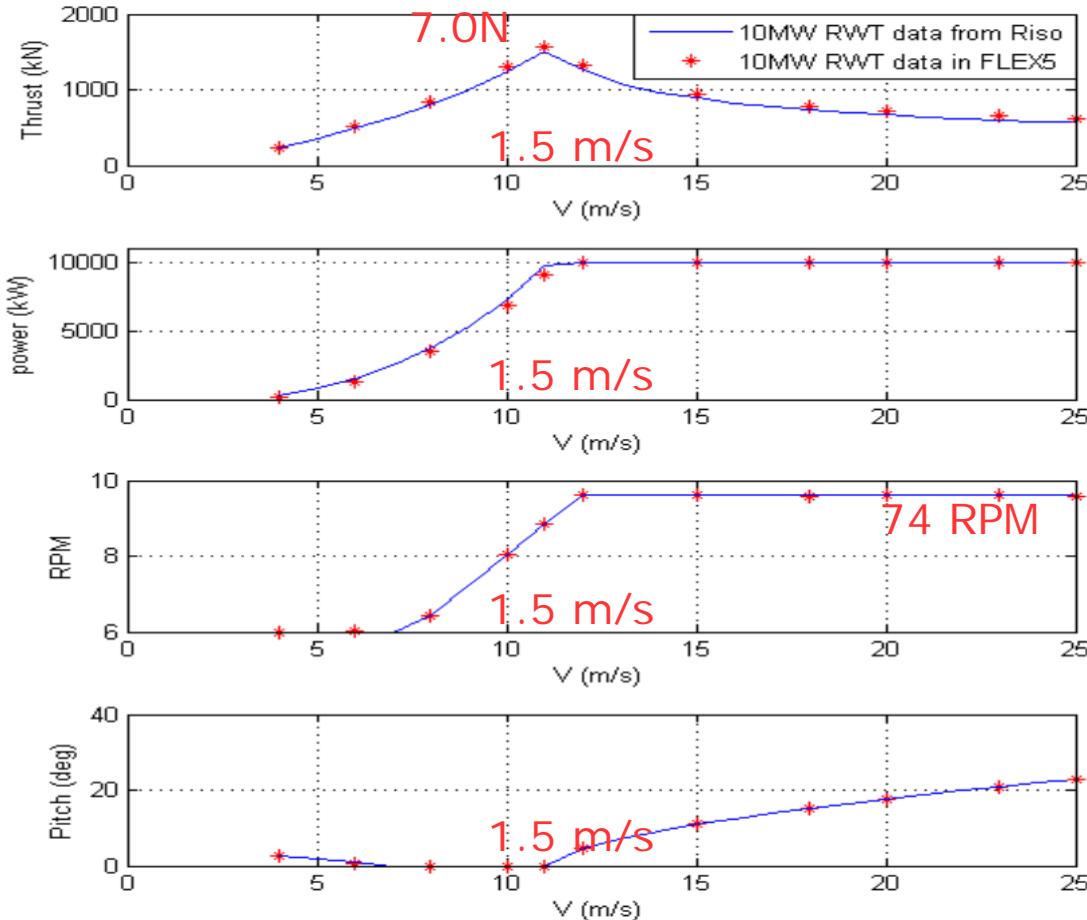


The Triple  
Spar floater

## Results

Re-n

Co  
na  
ro



## DTU 10MW reference WT

### Froude scaling:

Length  $\sim \lambda$   
Time  $\sim \lambda^{1/2}$   
Velocity  $\sim \lambda^{1/2}$

### Air velocities

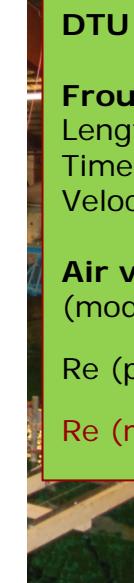
(model scale)  $\sim 1.5$  m/s

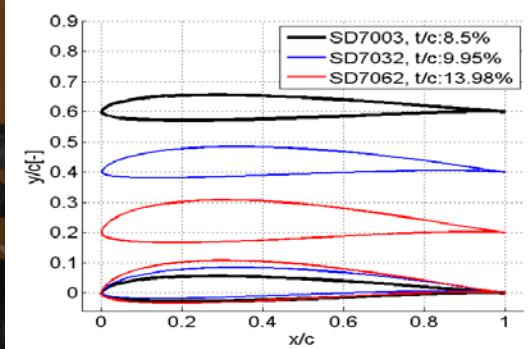
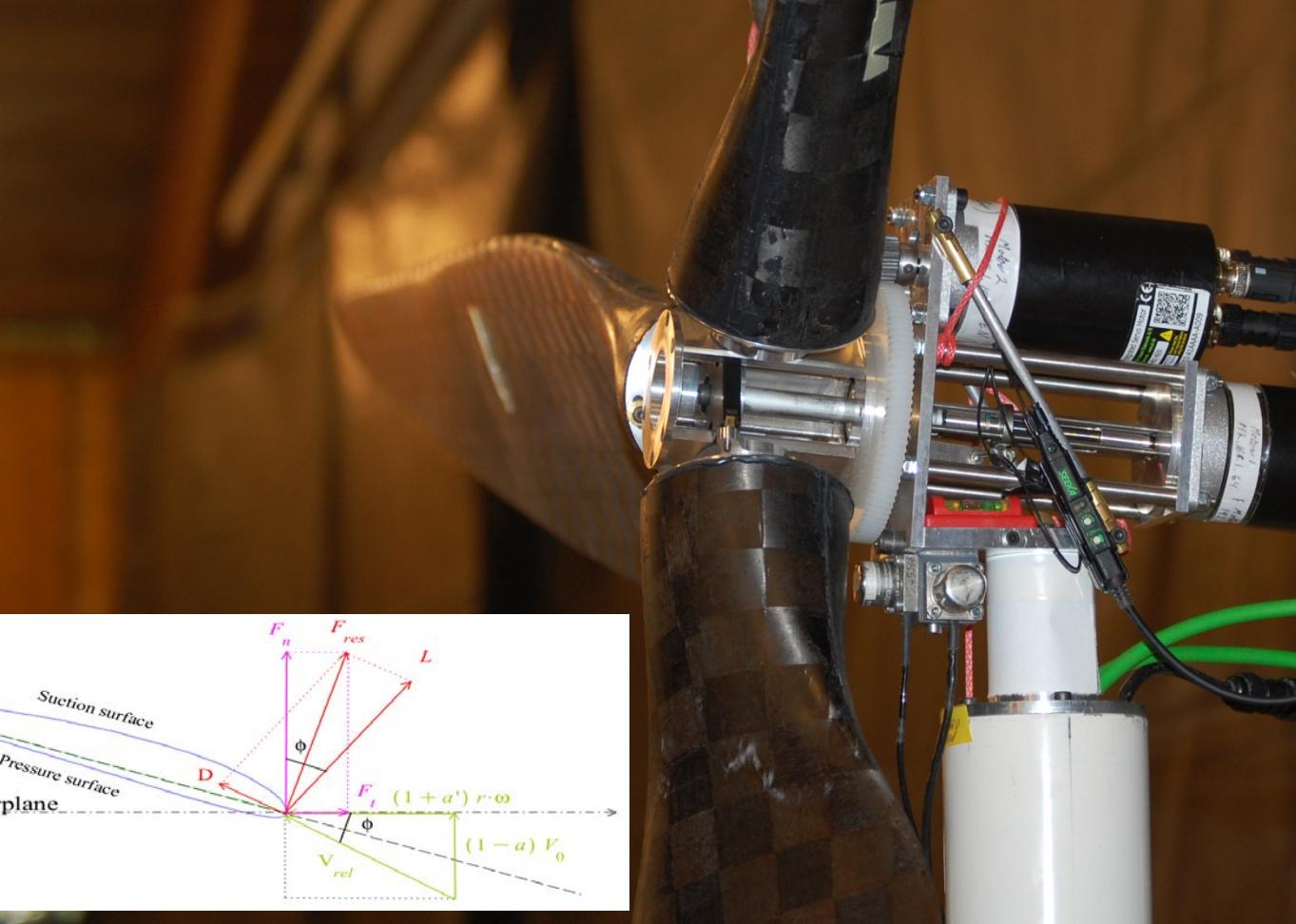
Re (proto scale)  $\sim 10M$

Re (model scale):  $\sim 25k$

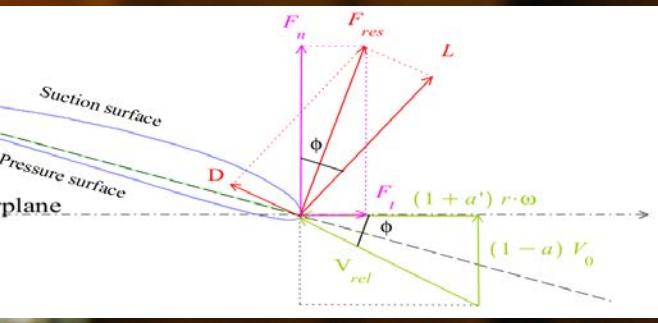
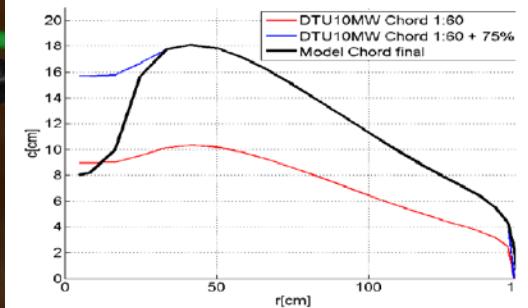


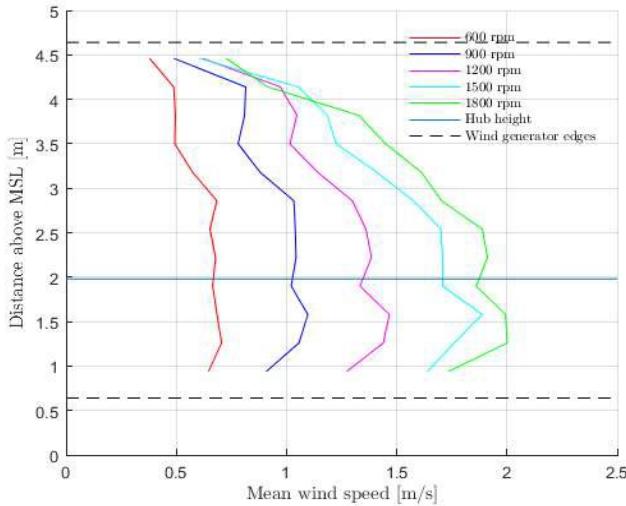
Rotor  
design



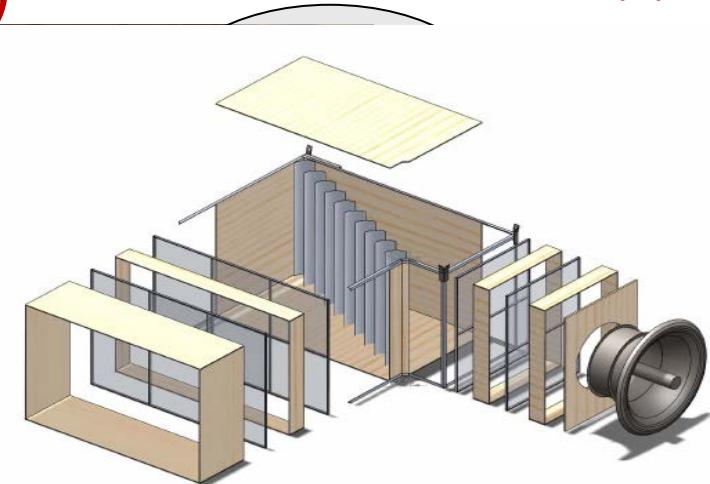


Low Re airfoils  
75% increased chord





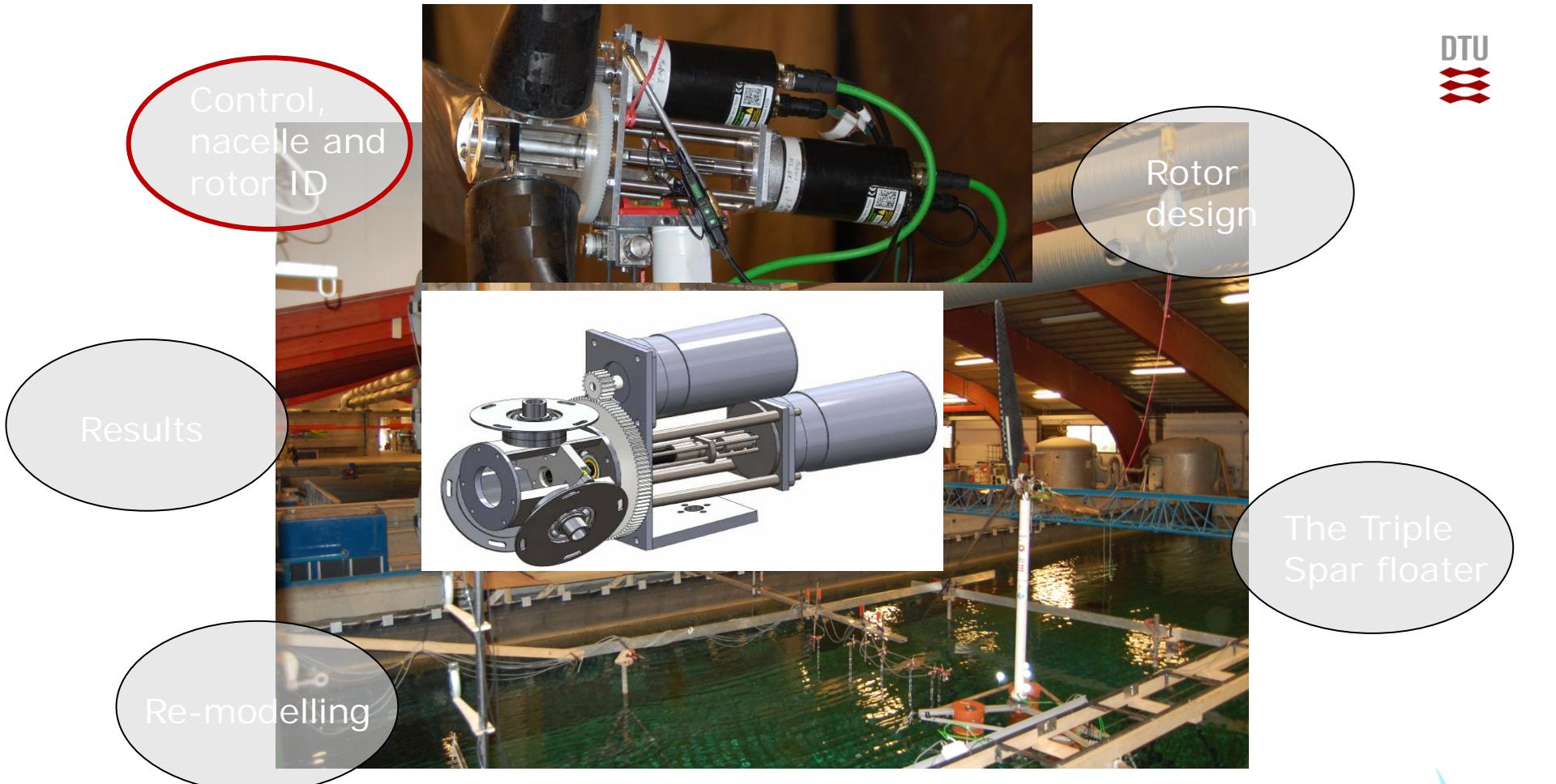
Wind climate  
and waves



Triple  
air 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 !



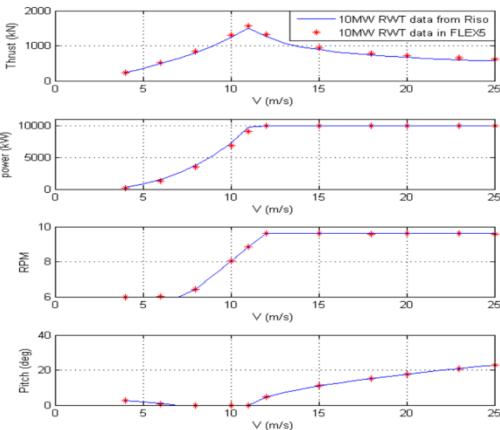
Control,  
nacelle and

## Rotor ID

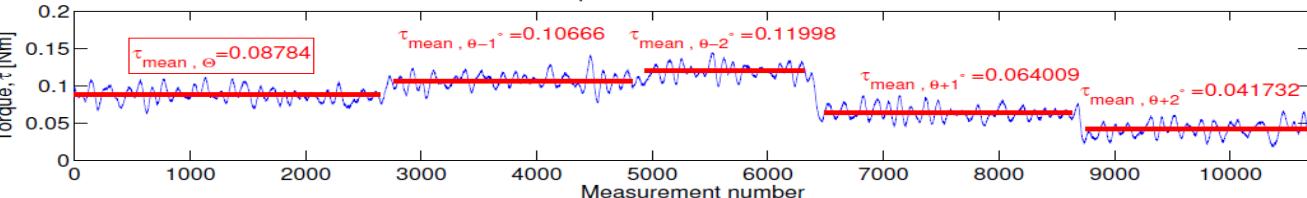
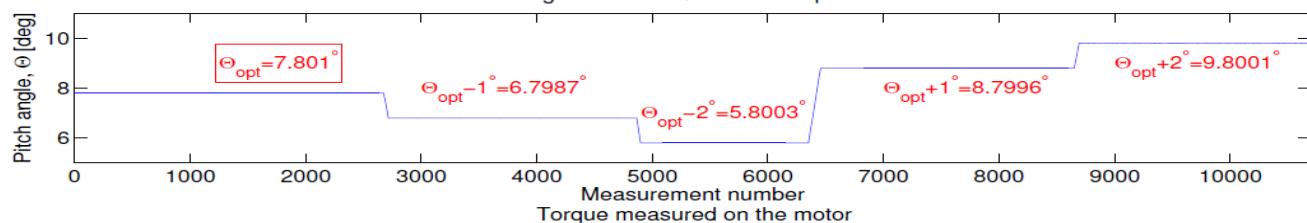
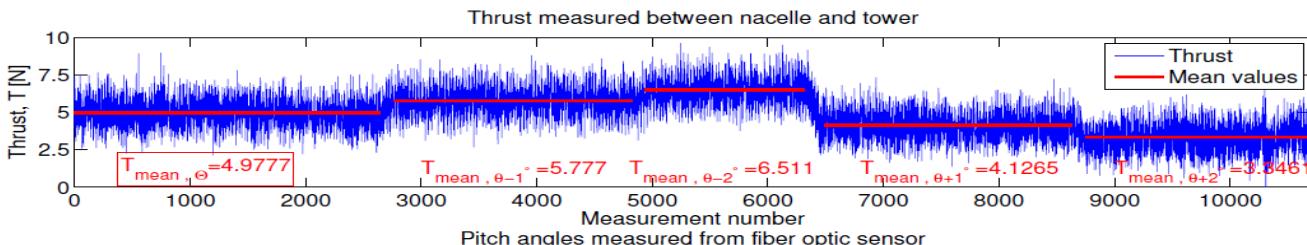
Wind speed -> rotor speed

Measure thrust and torque vs  
blade pitch

Gives desired blade pitch



Thrust measured between nacelle and tower



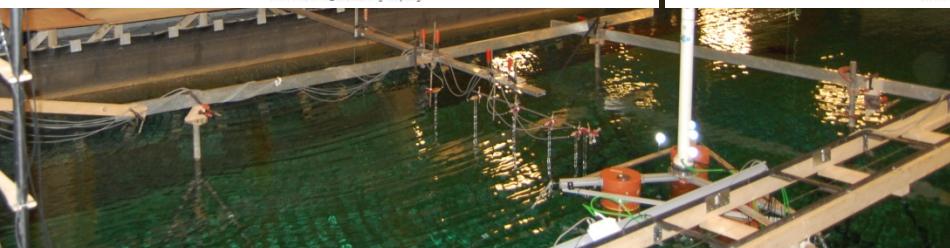
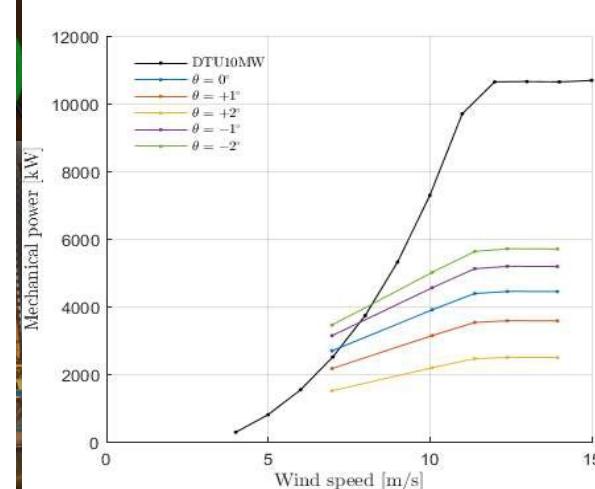
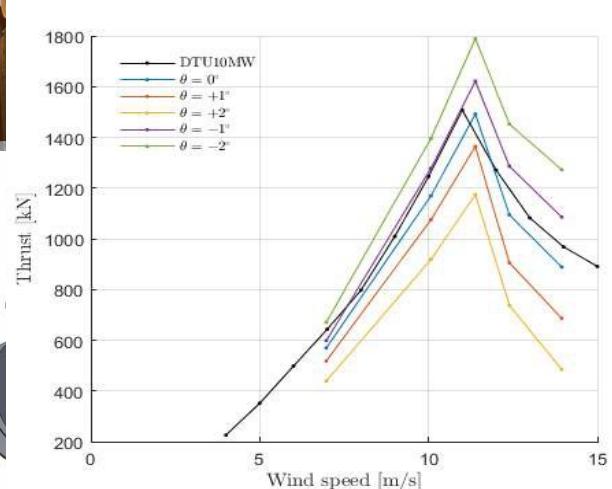
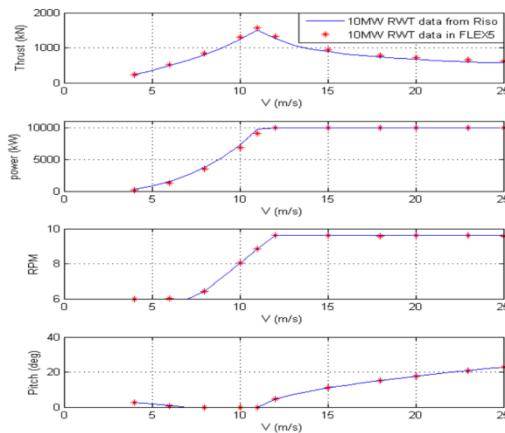
Control,  
nacelle and

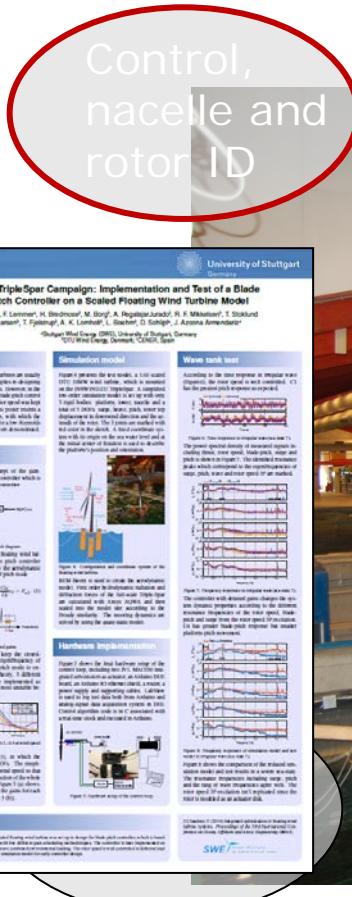
## Rotor ID

Wind speed -> rotor speed

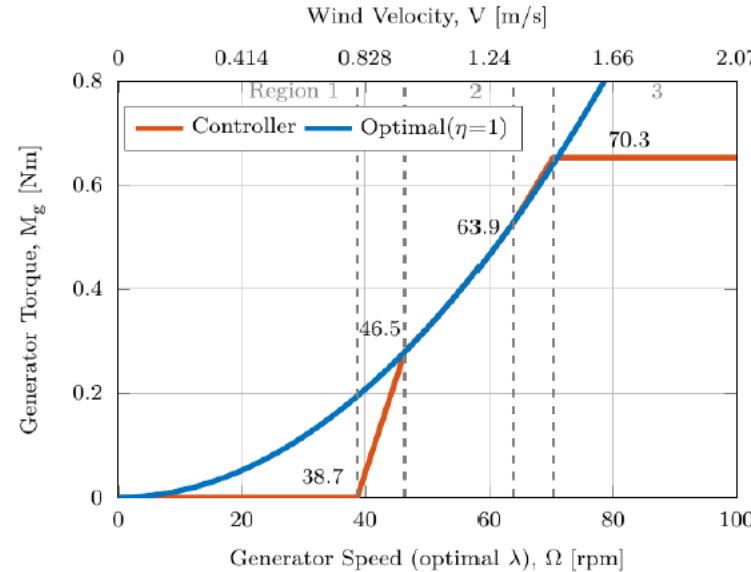
Measure thrust and torque vs  
blade pitch

Gives desired blade pitch





# SWE Model-in-The-Loop → Torque controller



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

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

Optimal Cp tracking

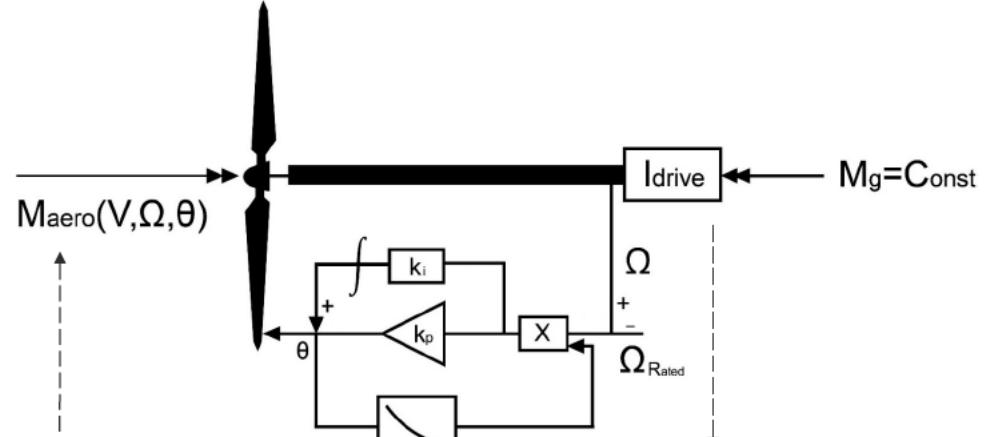
$$\frac{\rho \cdot A \cdot C_P \cdot R^3 \cdot \Omega^2}{2 \cdot \lambda^3} \xrightarrow{\eta}$$

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

[Yu Wei, SWE]

Regulate motor torque to get optimal Cp

## Model-in-The-Loop → Pitch controller (1/3)



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

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

Pitch sensitivity varies

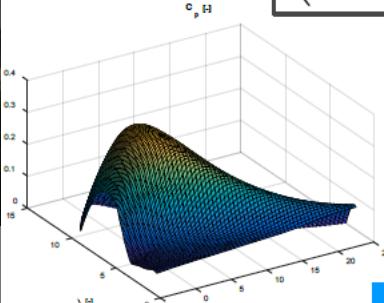
[Yu Wei, SWE]

Regulate blade pitch to get constant rotational speed

Control,  
nacelle and  
rotor ID

Results

Re-modelling

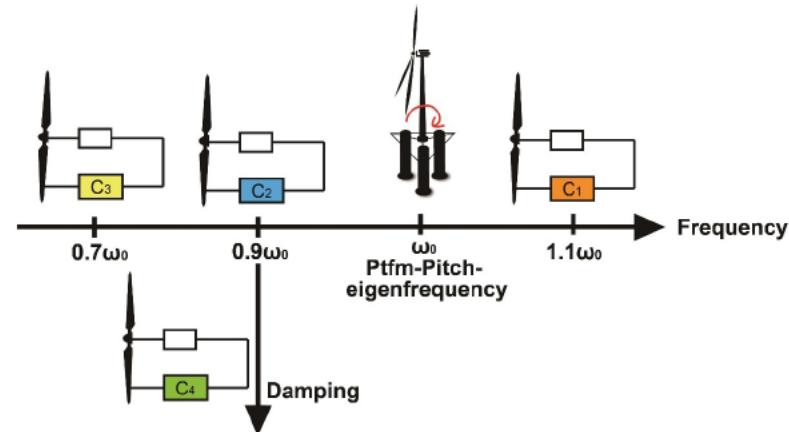
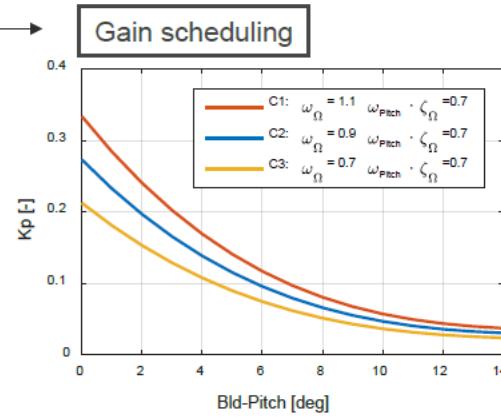
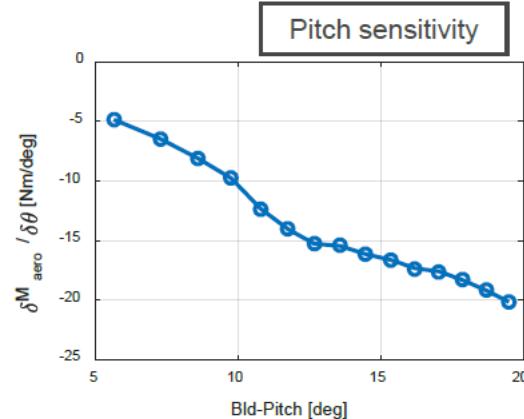


Control,  
nacelle and  
rotor ID

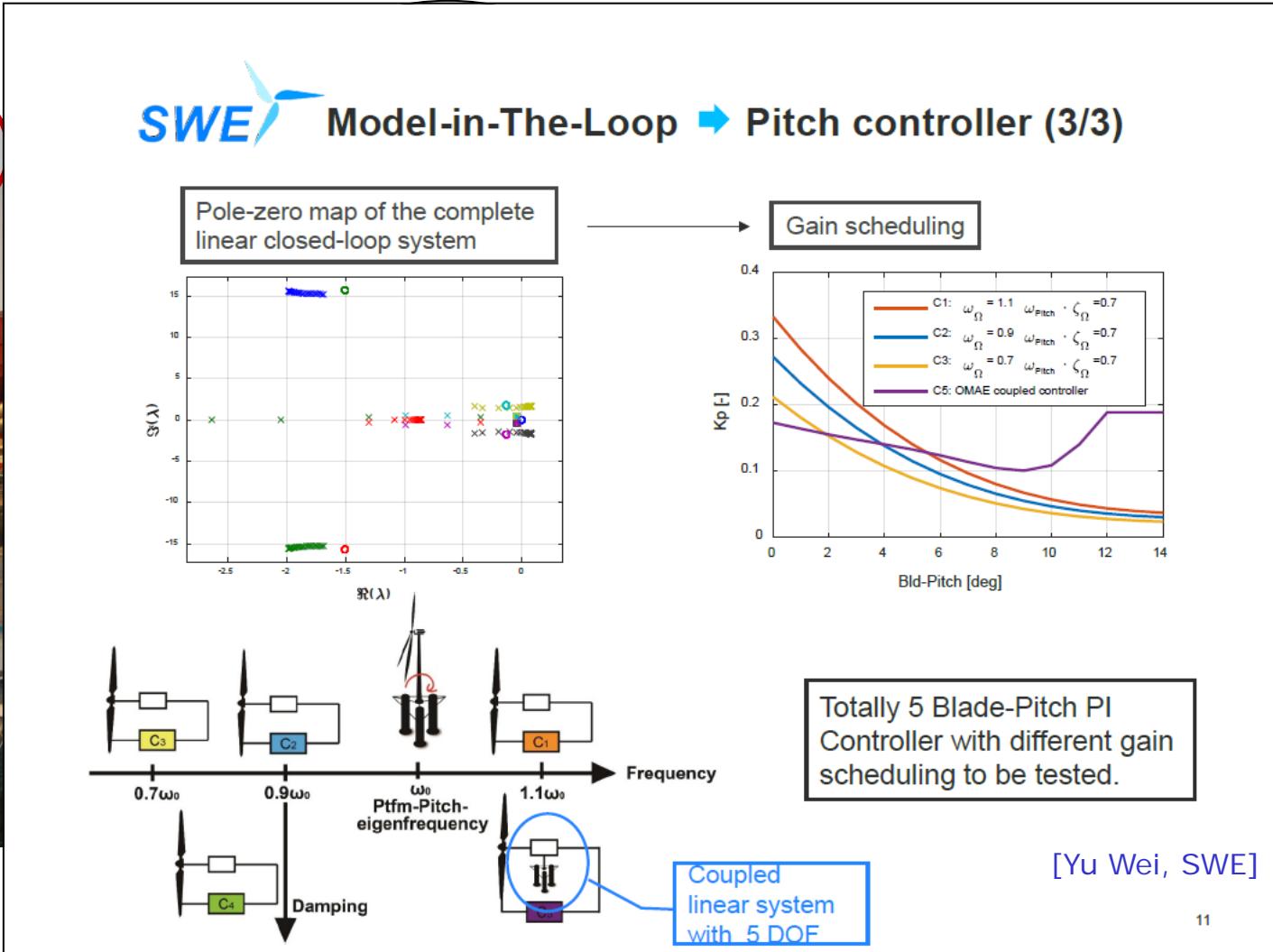


Results

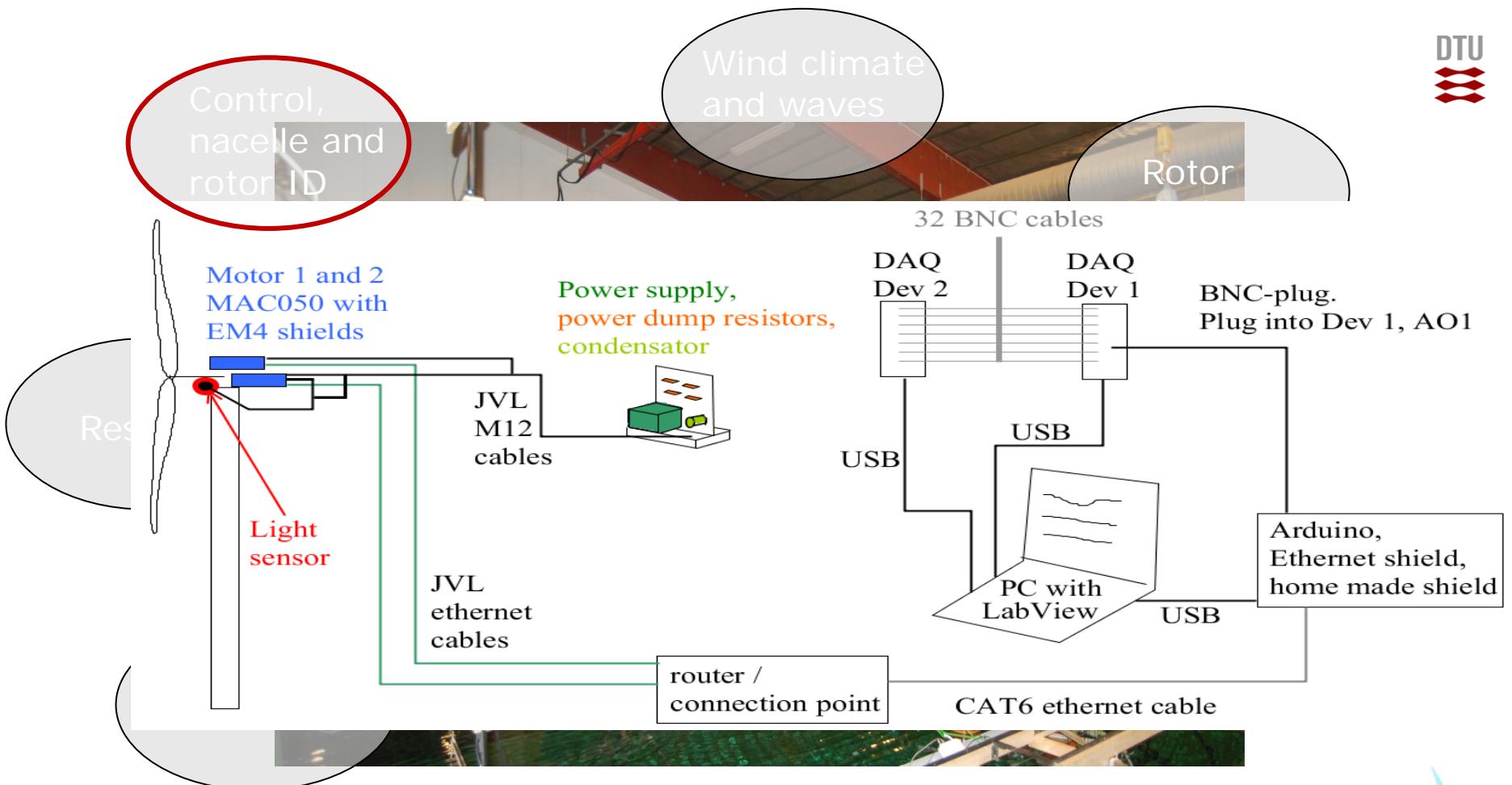
Re-modelling

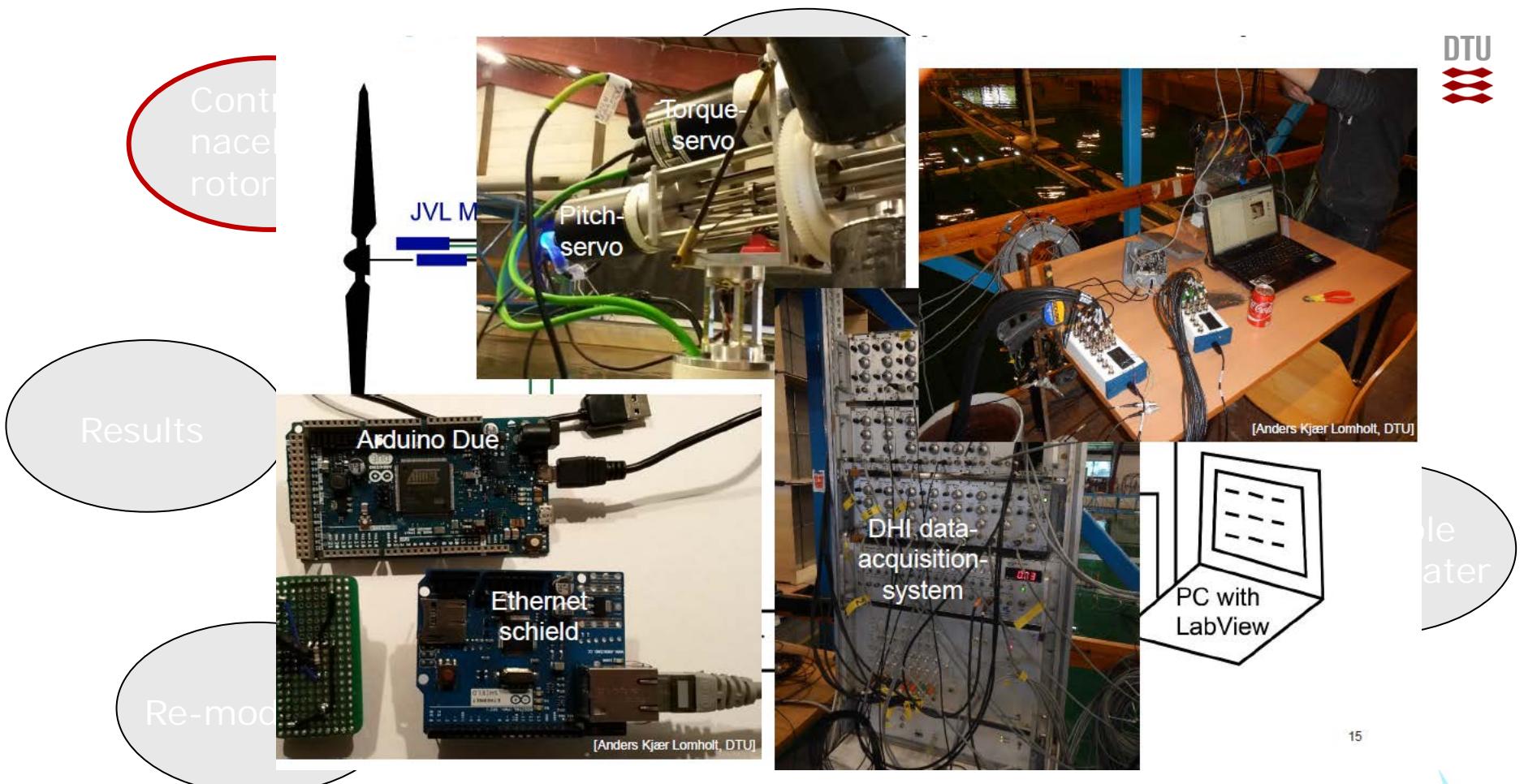


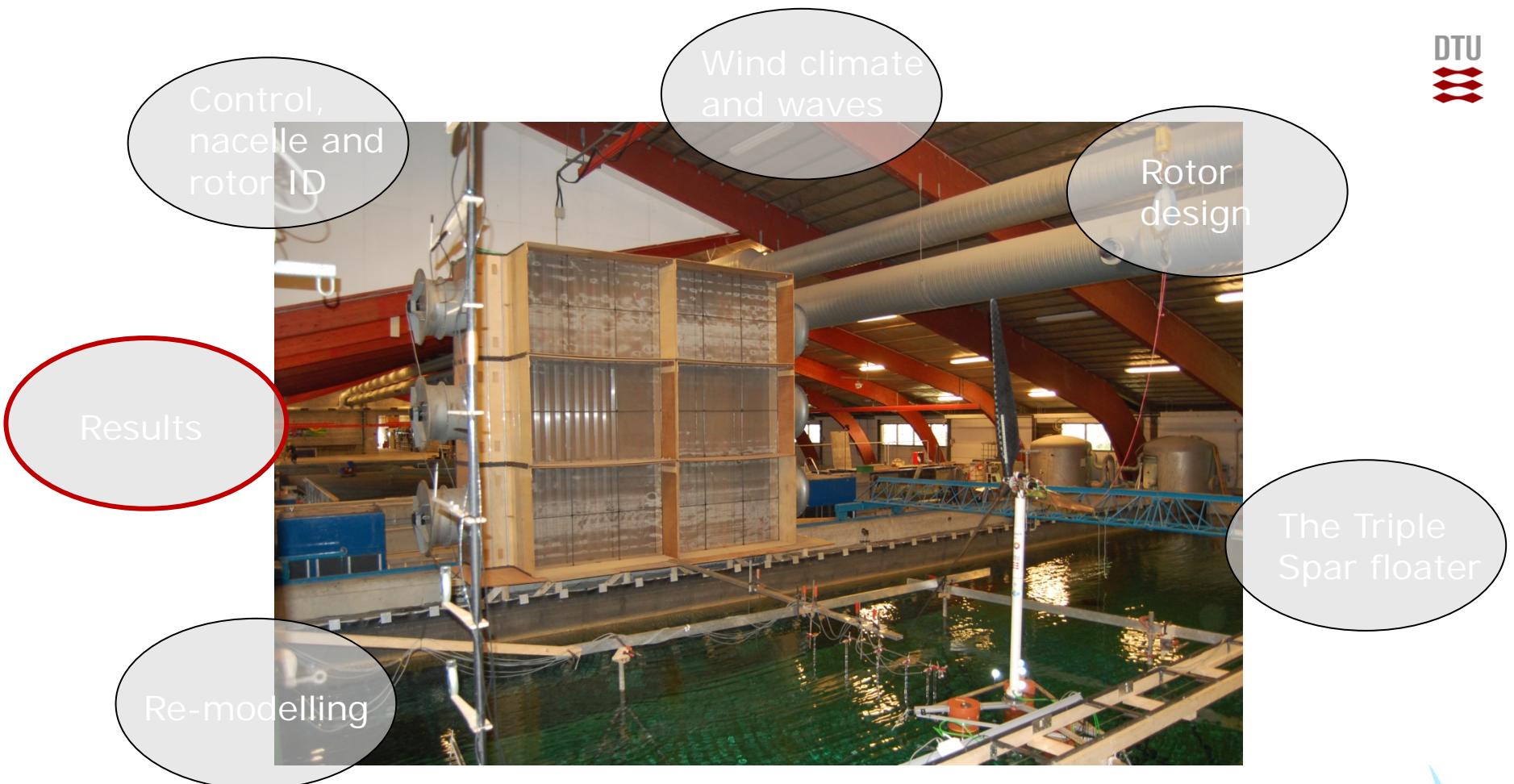
How does the eigenfrequency  
of the drivetrain closed-loop  
affect the system dynamic?



[Yu Wei, SWE]





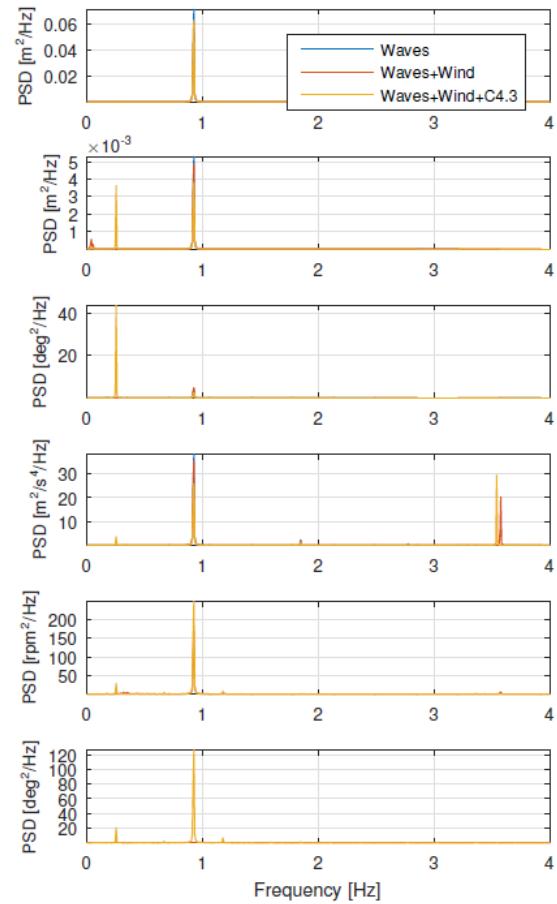
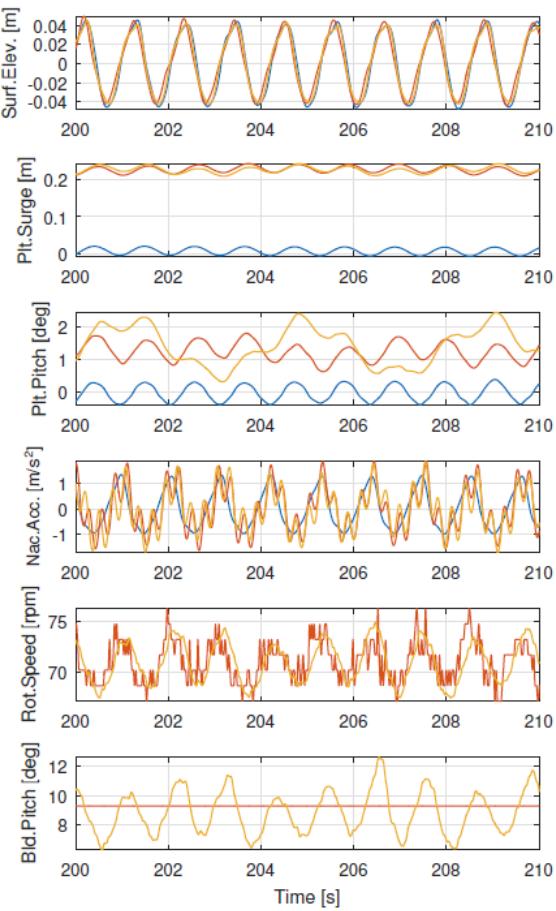


## Regular waves

Results



Re-modelling



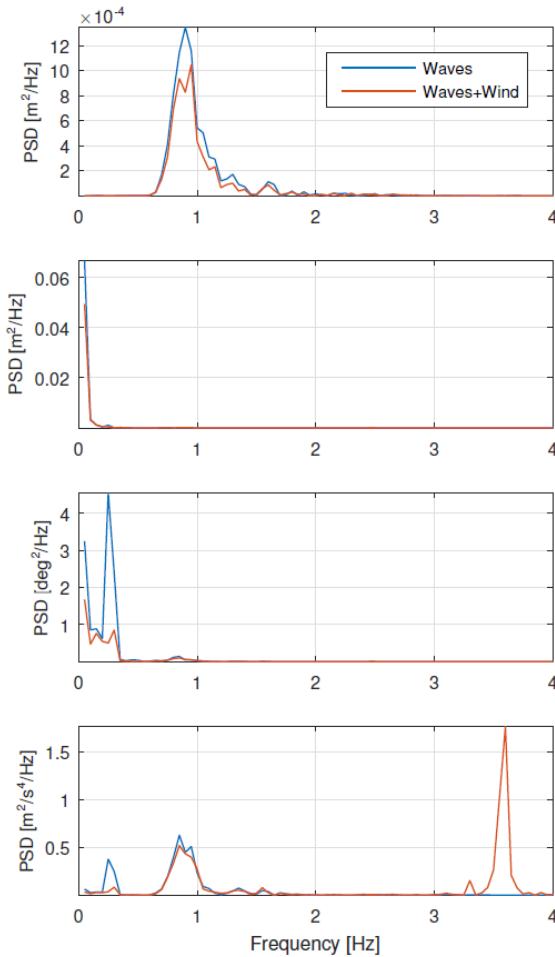
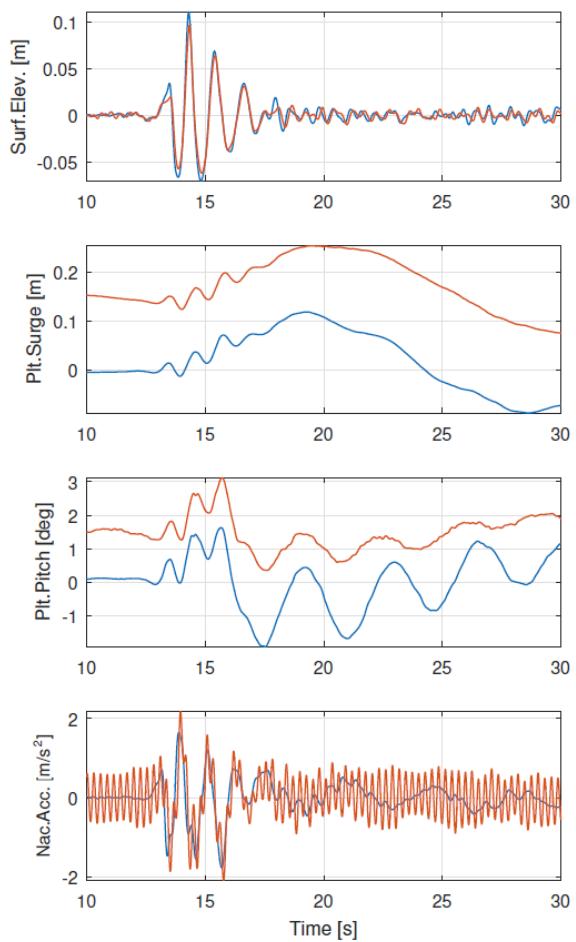
e  
water

## Focused wave



Results

Re-modelling

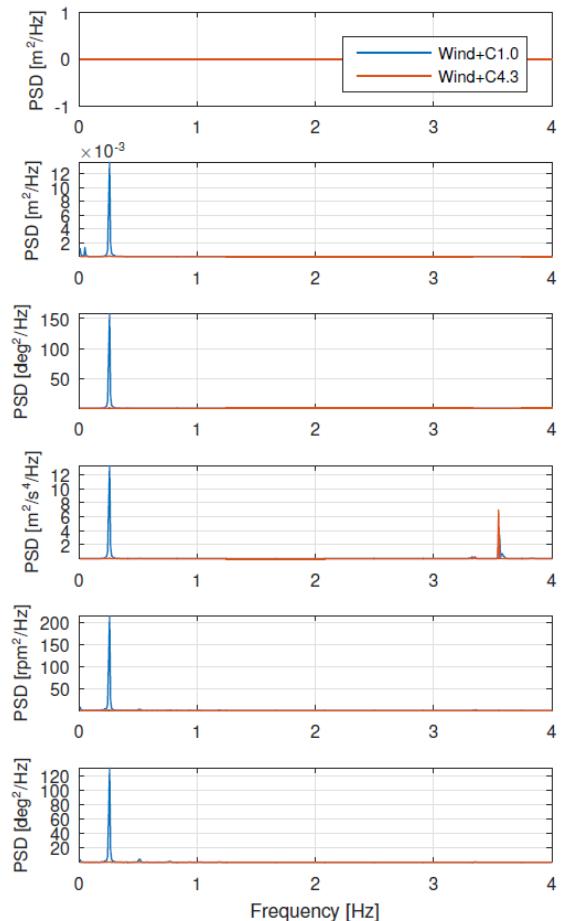
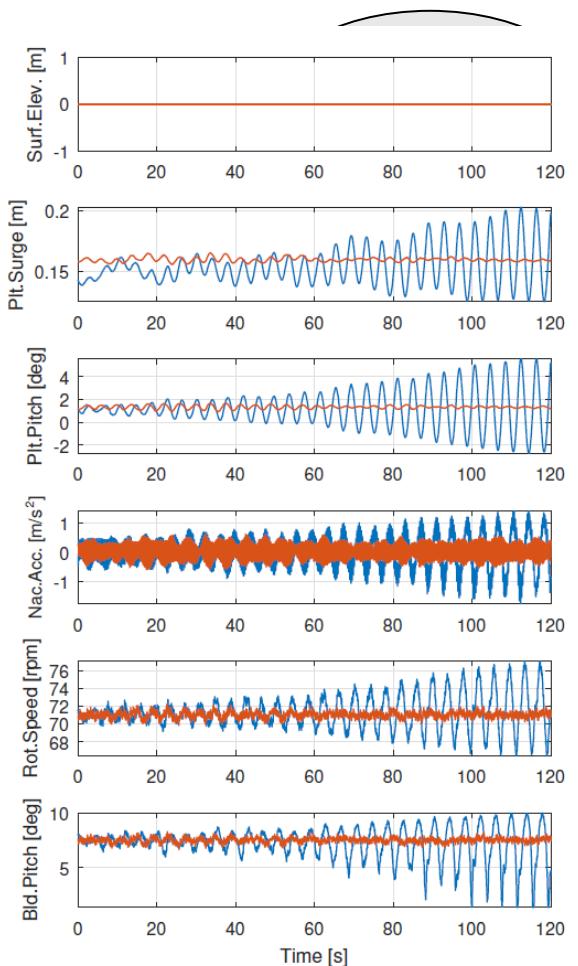


# Platform pitch instability

Results



Re-modelling



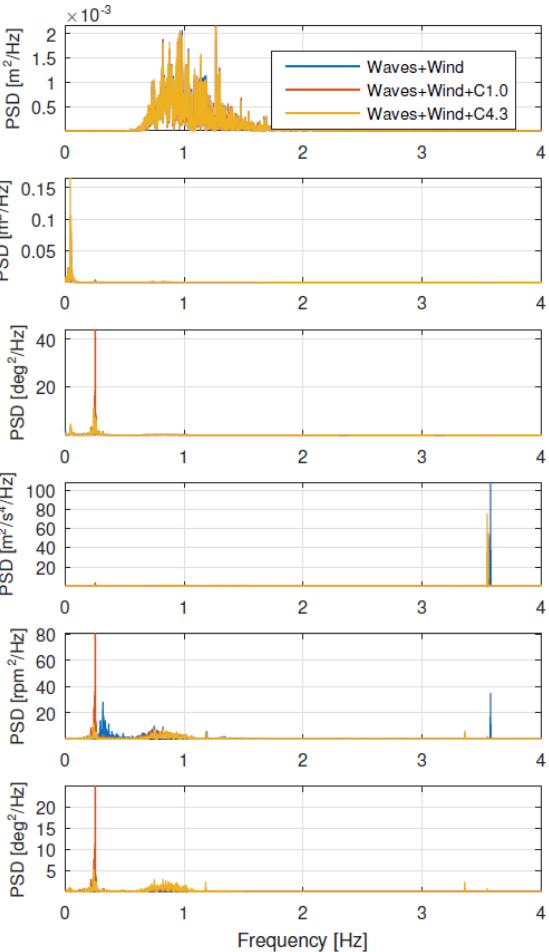
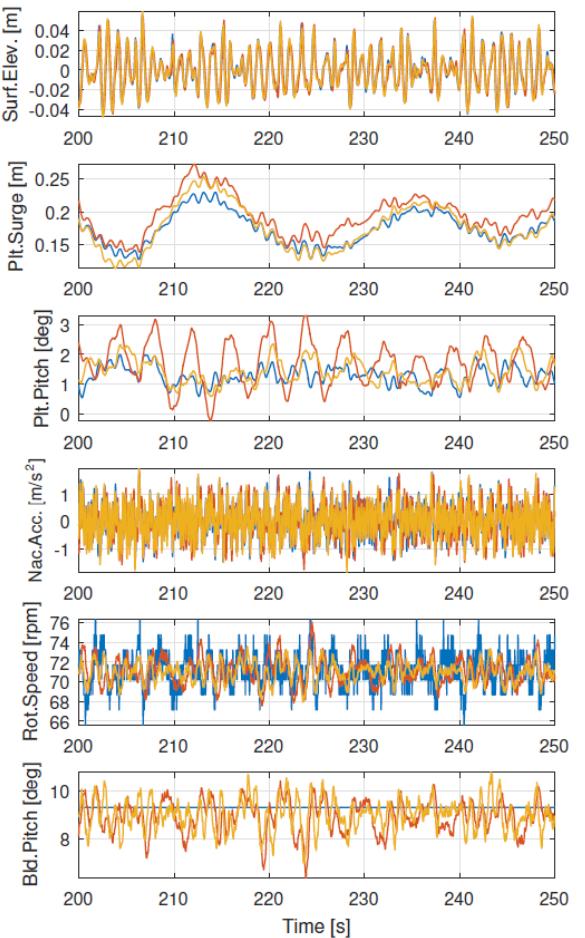
e water

# Irregular waves

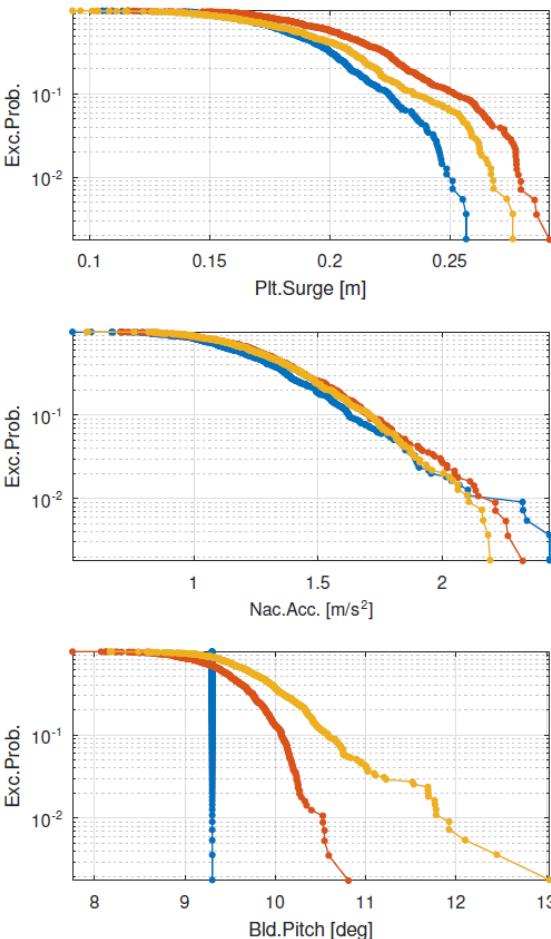
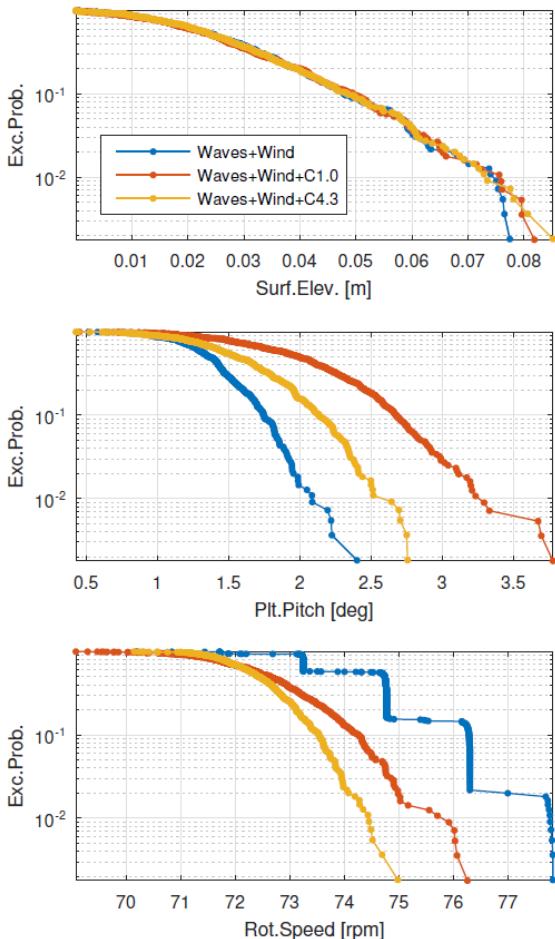
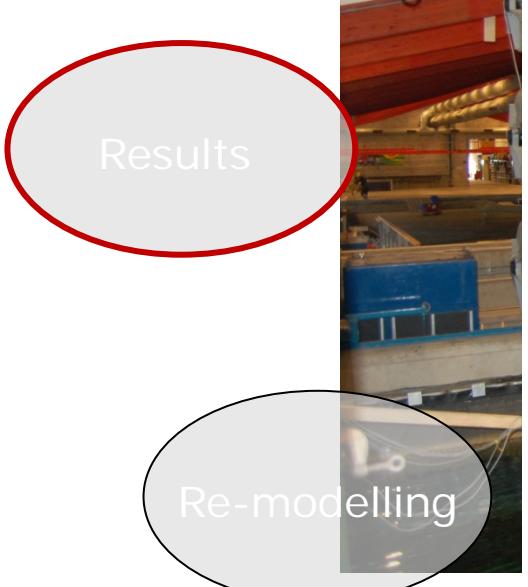
Results

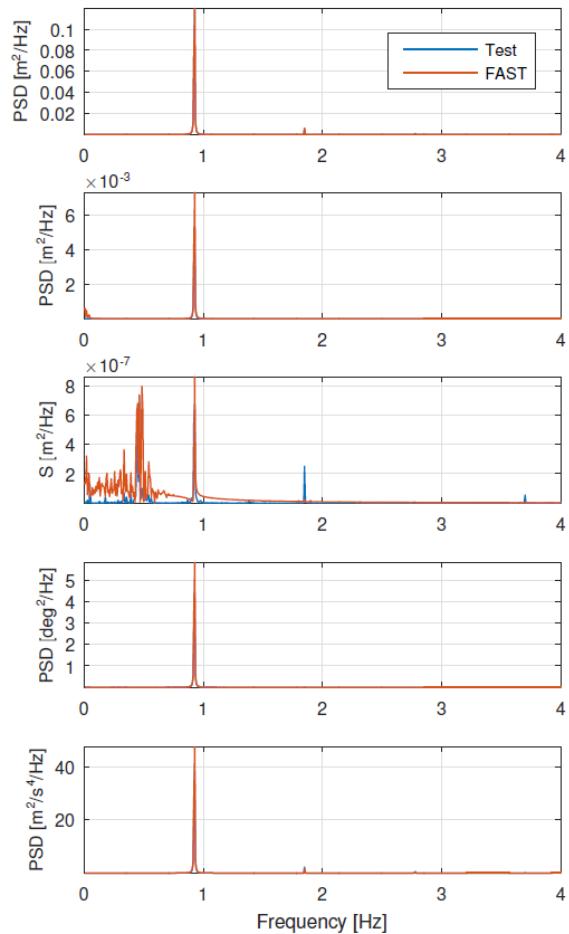
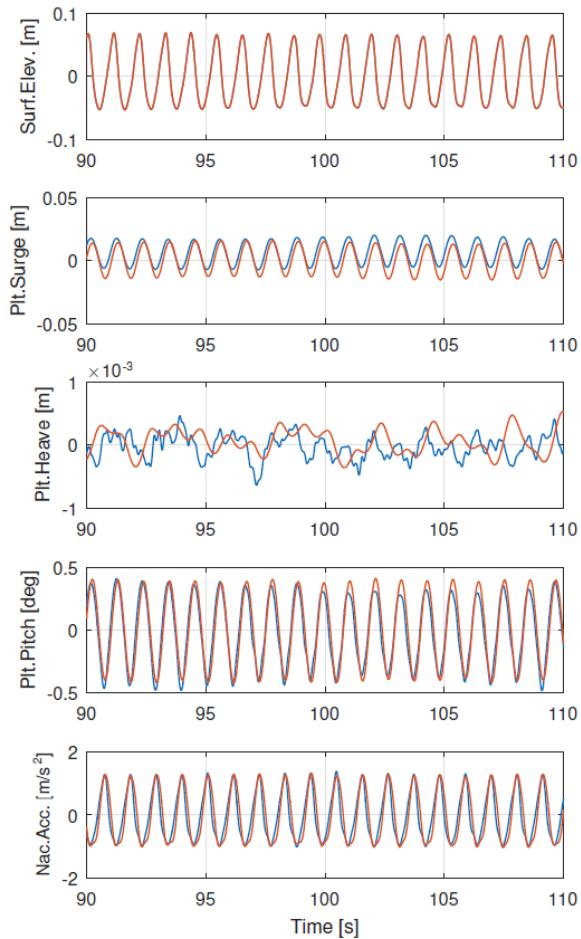
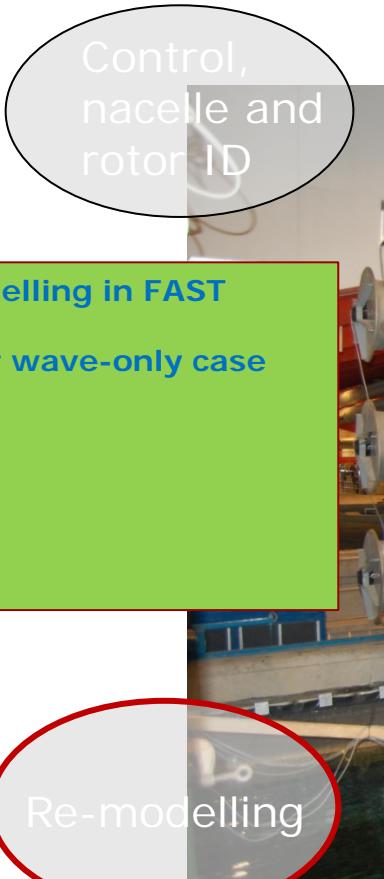


Re-modelling



## Irregular waves





le  
water

