Model testing of a floating wind turbine including control

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EERA DeepWind'2017

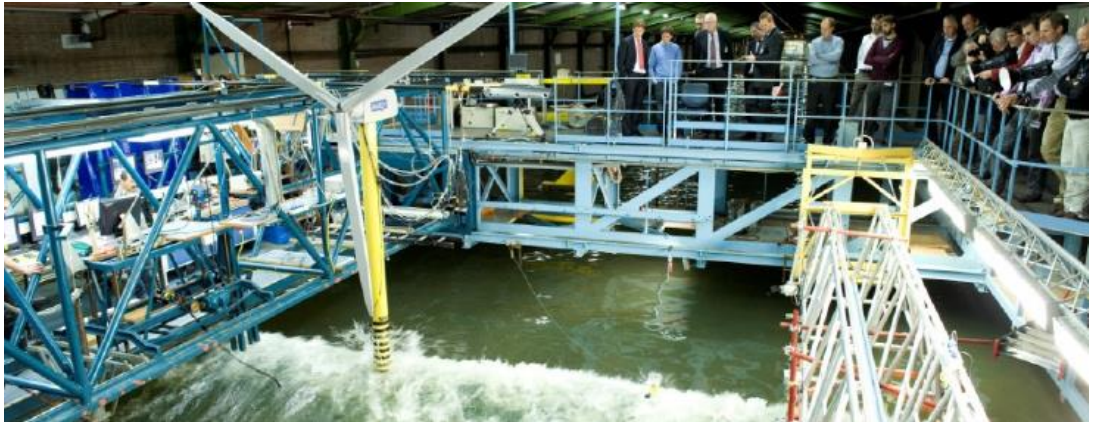
Trondheim, 2017/01/19

Contents

Introduction (1)

Physical model test of floating offshore structures are common practice:

- Calibration of the numerical model
- To investigate phenomena that are difficult to capture with numerical methods
- (Visual) feedback on the behavior of the total system in wind and waves



Breaking wave on monopile foundation from MARINs
WiFi model test campaign

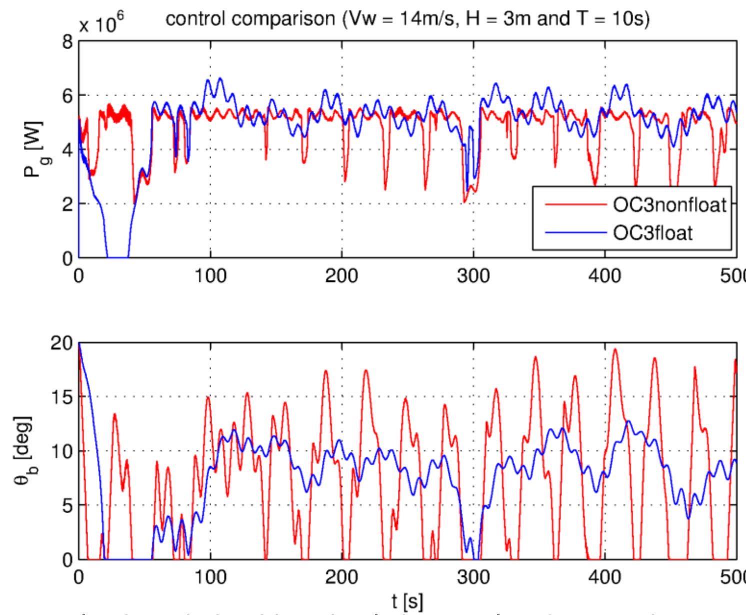
Introduction (2)

Earlier studies showed the large impact of the wind turbine controller on the floating wind turbine behavior:

- Operational curve (thrust)
- Limit cycling with closed loop blade pitch control

Several methods to included the wind turbine (with controller) are under investigation:

- Model scale wind turbine
- Hardware in the loop (tension rod / fan)



Floating wind turbine simulation results of a stepwise increasing wind speed with two different controllers; one conventional and one tuned for floating to prevent limit cycling due to interaction with floater pitch motion.

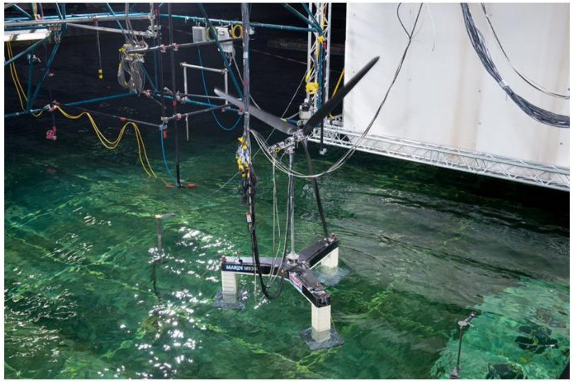
Introduction (3)

A model test campaign of the Tri-Floater concept (GustoMSC, MARIN, ECN) in 2011 showed:

- Importance of the correct wind turbine characteristics at model scale
- Wind turbine control that mimics full scale behavior is possible, but there are challenges to further investigate

New model test campaign in the TO2 project 'Floating Wind Energy', with focus on:

- Effects of narrow wave basin on system behavior in the dominant direction
- Floating wind turbine control at model scale



GustoMSC Tri-Floater campaign in MARINs Offshore wave basin

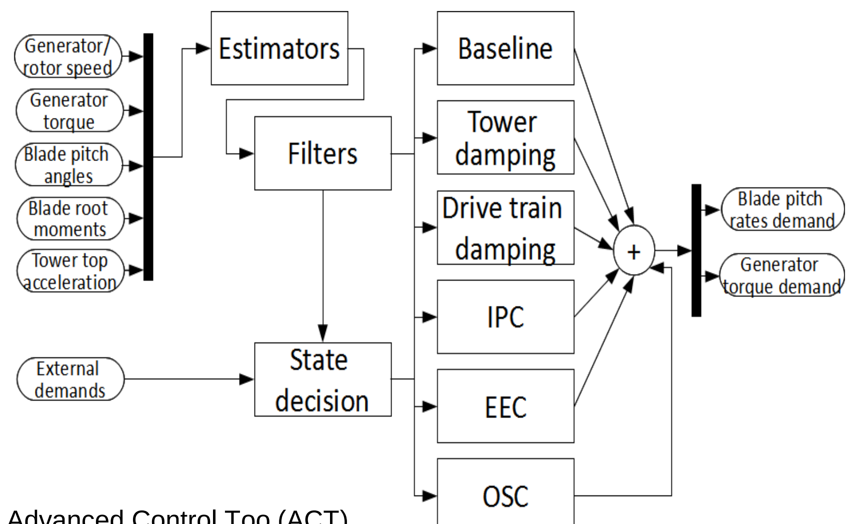
Control design at model scale (1)

Challenges when moving to model scale:

- How to determine the rotor characteristics?
- How to deal with low Reynolds number, low power coefficient, highly 3D flow on the blades

Basic PI-controller design to mimic full scale behavior, including:

- Gain scheduling
- Peak shaving
- Stall shaving
- Controller gains

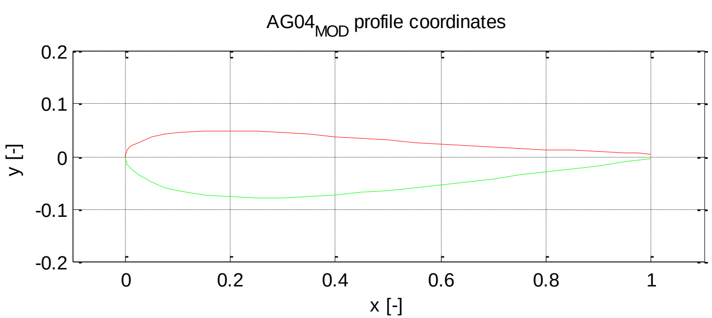


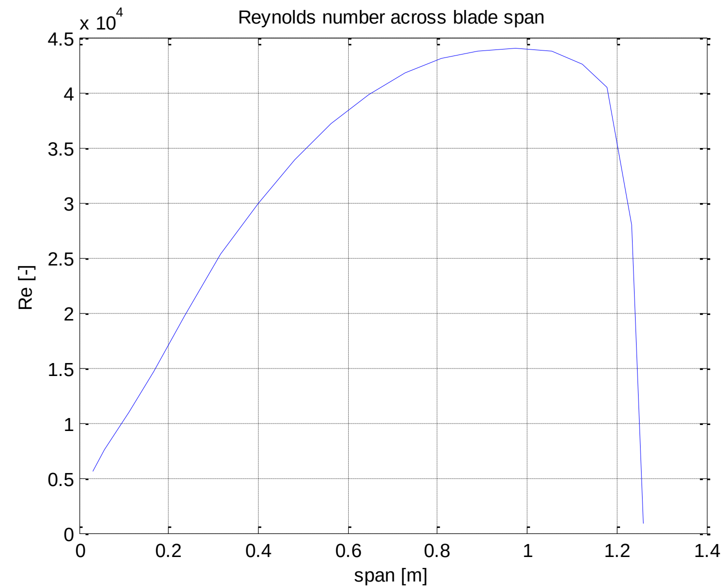
ECN Advanced Control Too (ACT)

Control design at model scale (2)

How to capture the rotor characteristics:

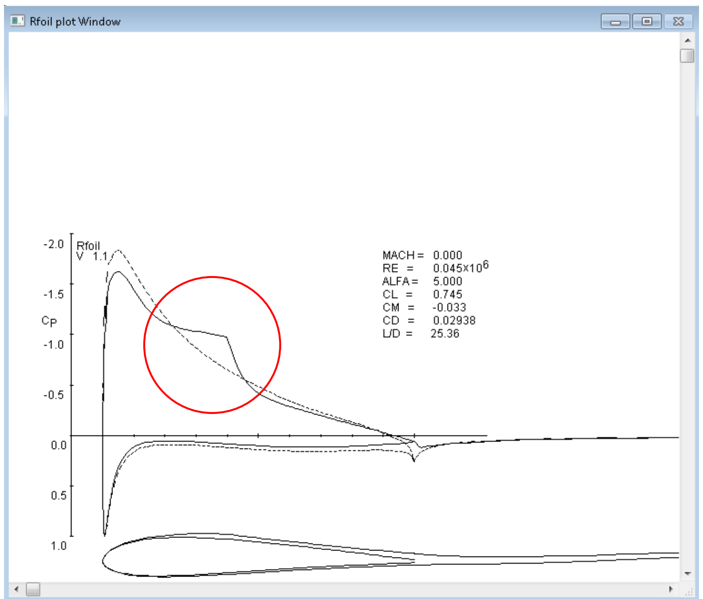
- Measure on the actual system
- Calculate with numerical model (low Reynolds number!)



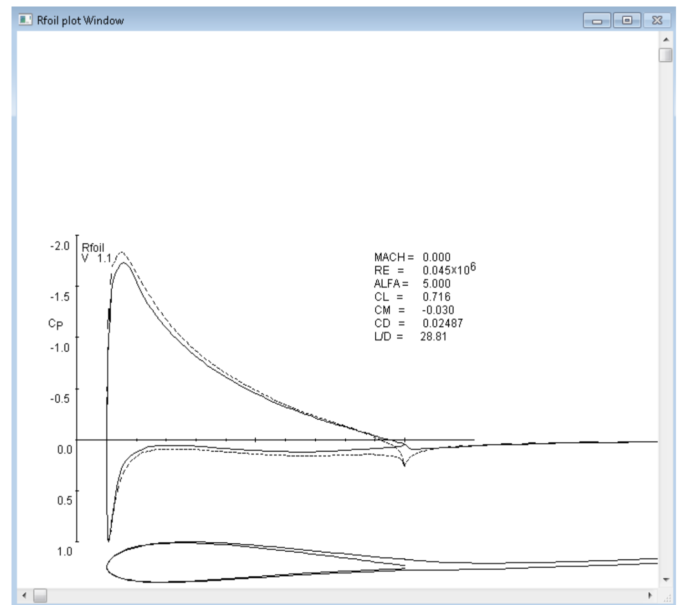


Control design at model scale (3)

RFOIL calculations show laminar seperation for low Re (45k)



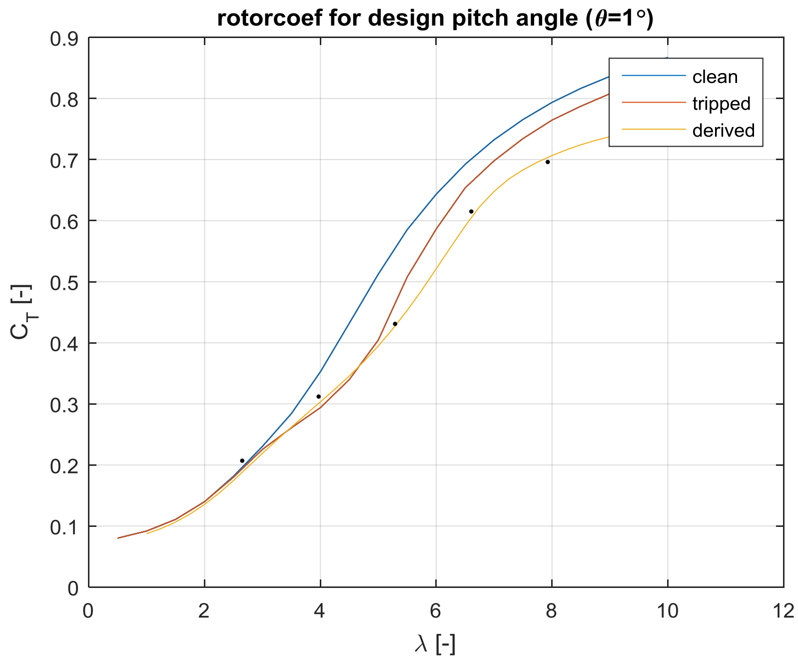
RFOIL calculation with clean AG04mod airfoil

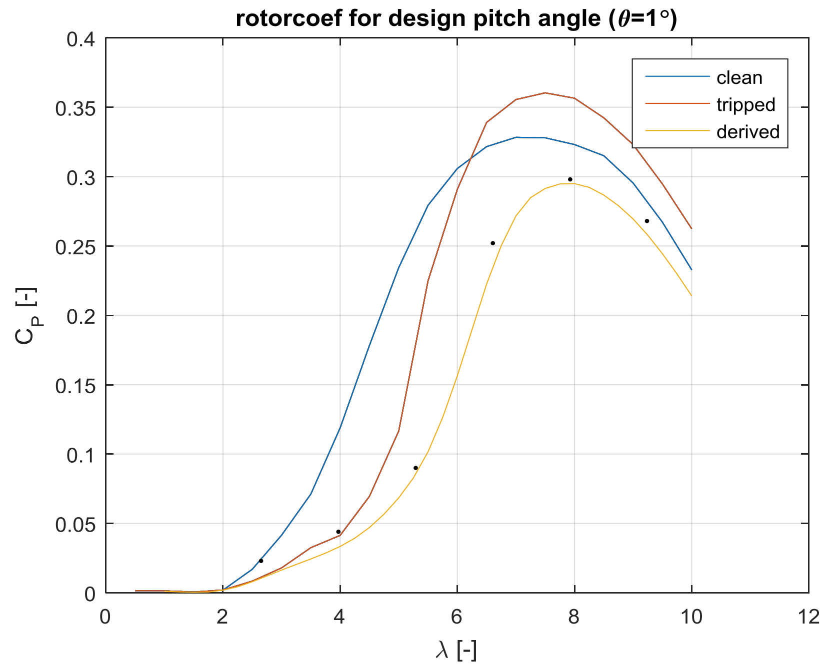


RFOIL calculation with 5% tripped AG04mod airfoil

Control design at model scale (4)

Predicted, derived[1] and measured characteristics:

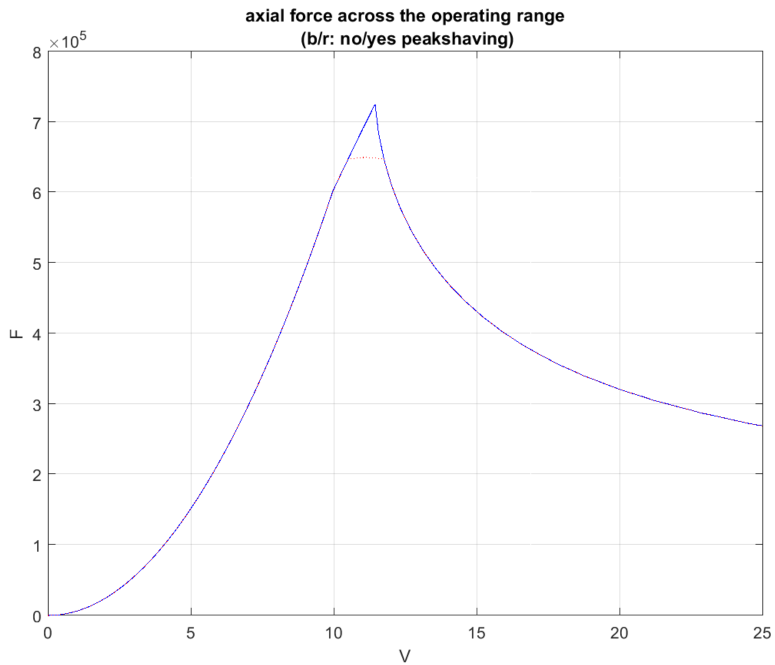




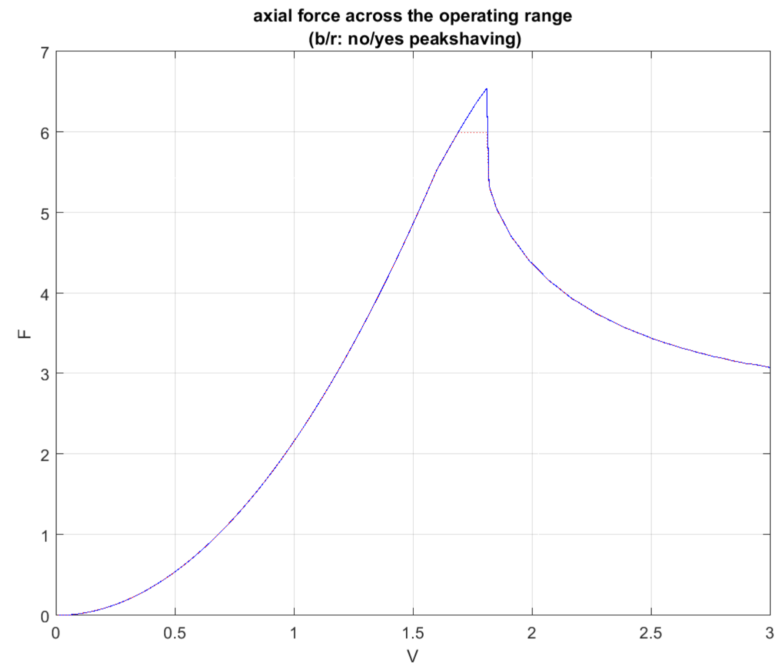
[1] Goupee, A. J.; Kimball, R. W.; de Ridder, E.; Helder, J.; Robertson, A. N.; Jonkman, J. M. (2015). "A Calibrated Blade-Element/Momentum Theory Aerodynamic Model of the MARIN Stock Wind Turbine". OMAE Conference, June 2015.

Control design at model scale (5)

Full scale



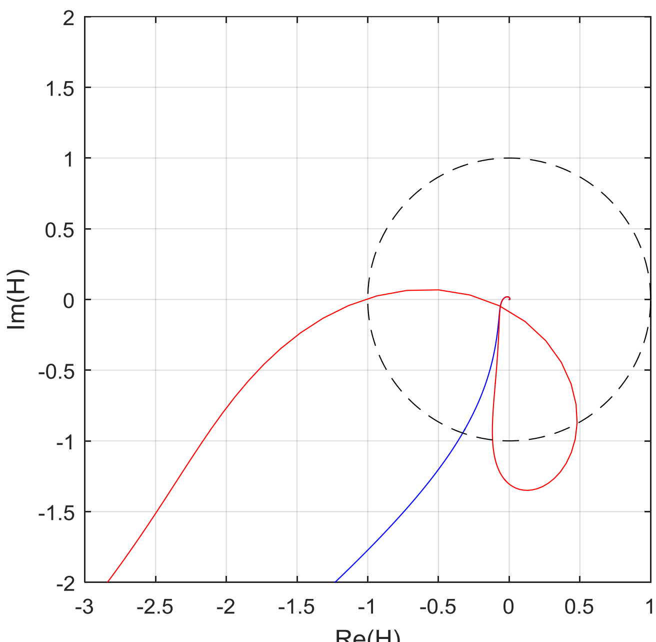
Model scale

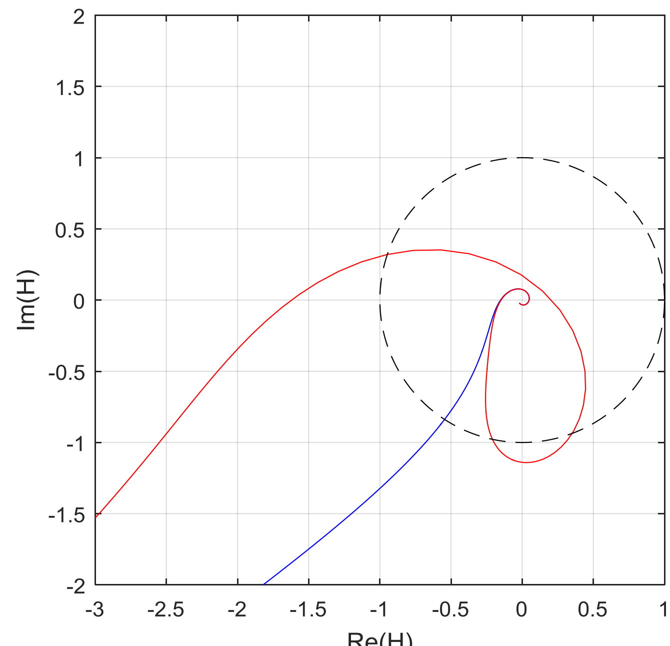


Control design at model scale (6)

Stability analysis of bottom-fixed controller

(full scale) (model scale)



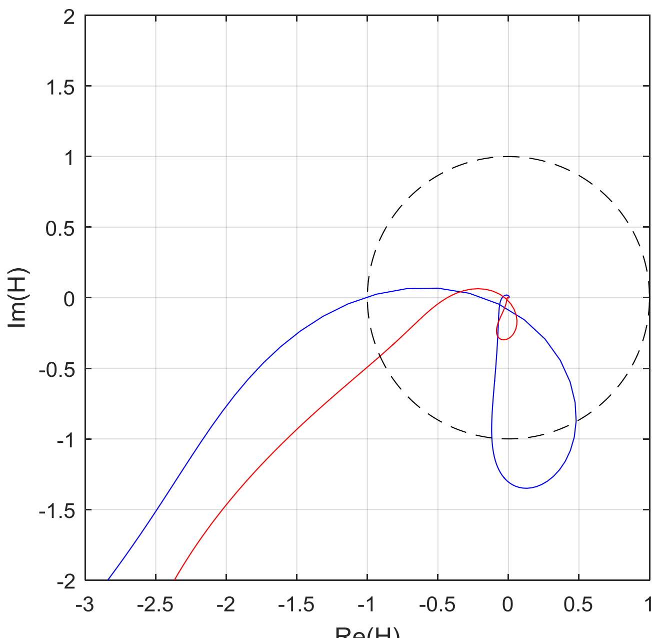


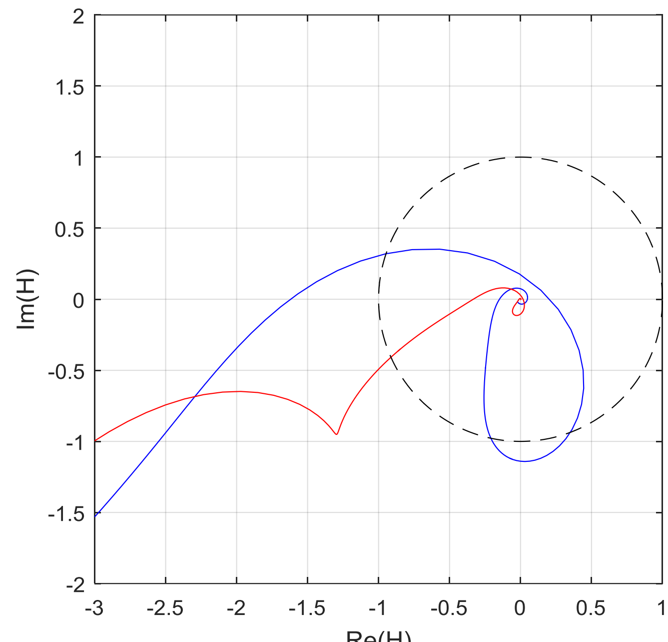
Nyquist plot to assess system stability (red: open loop, blue: closed loop with bottom-fixed controller)

Control design at model scale (7)

Similar solution for full scale and model scale (detune for lower bandwidth)

(full scale) (model scale)



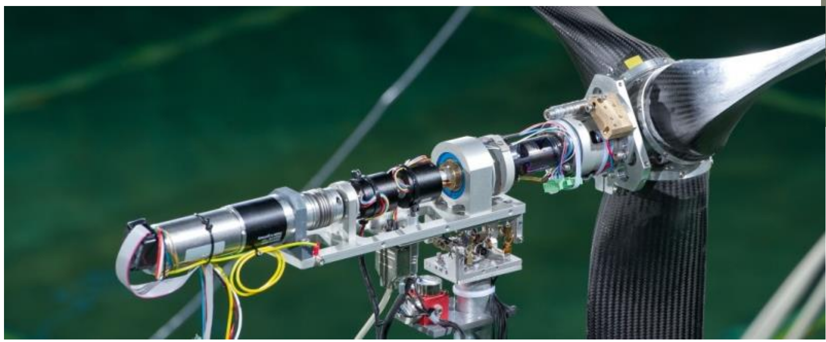


Nyquist plot to assess system stability (blue: closed loop with bottom-fixed controller, red: closed loop with detuned controller)

Model test campaign setup (1)

Overview of the campaign:

- Two weeks of testing November 2015
- MARIN concept basin, equipped with new wave and wind generators
- OC4 semi-submersible with the MSWT
- Dedicated mooring layout for narrow basin
- Three different controllers to be tested



Model test campaign setup (2)

Test cases with focus on controller interaction:

- Wind and wave calibration
- Constant and staircase wind
- Decay tests with and without control
- Limited number of operational cases (stochastic wind and irregular waves at rated and above rated)

Three different controllers have been tested:

[C1] fixed rotor speed, blade pitch scheduled with power

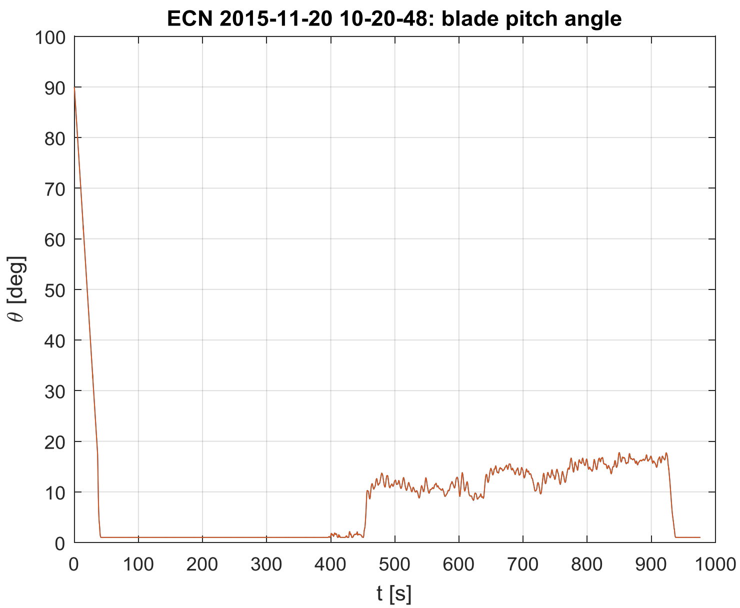
[C2] variable rotor speed, pitch to vane (tuned for bottom-fixed wind turbine)

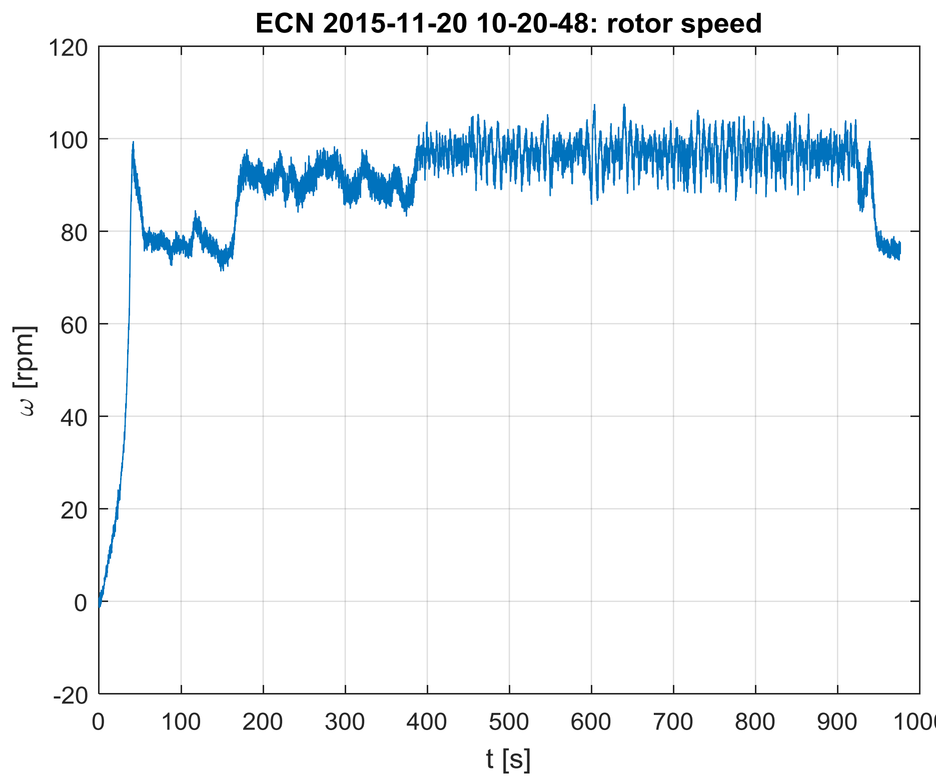
[C3] variable rotor speed, pitch to vane (tuned for floating wind turbine)

Model test results (1)

Staircase to verify:

- Rotor speed regulation
- Operational curve

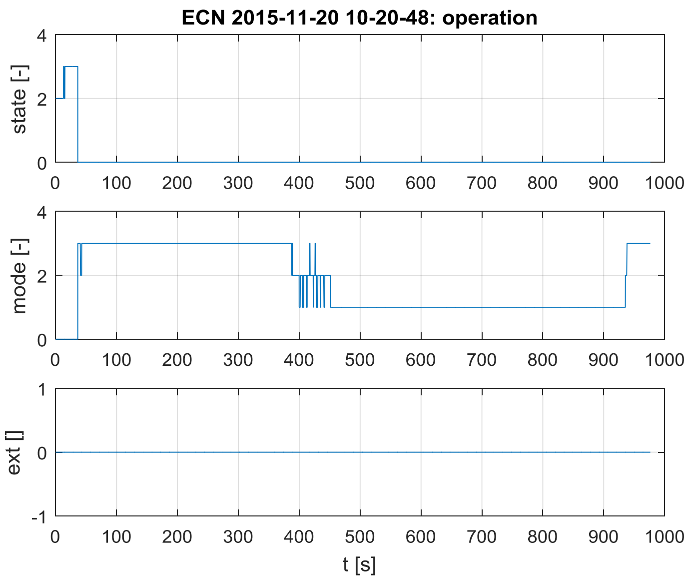


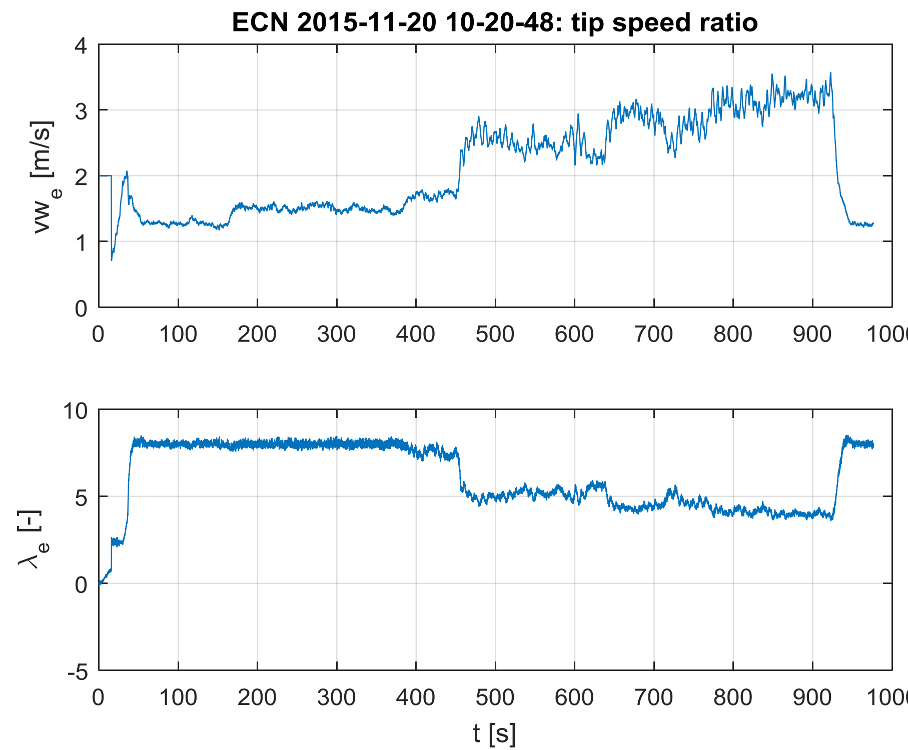


Model test results (2)

Staircase to verify:

- Wind speed estimation
- Partial/full load switching

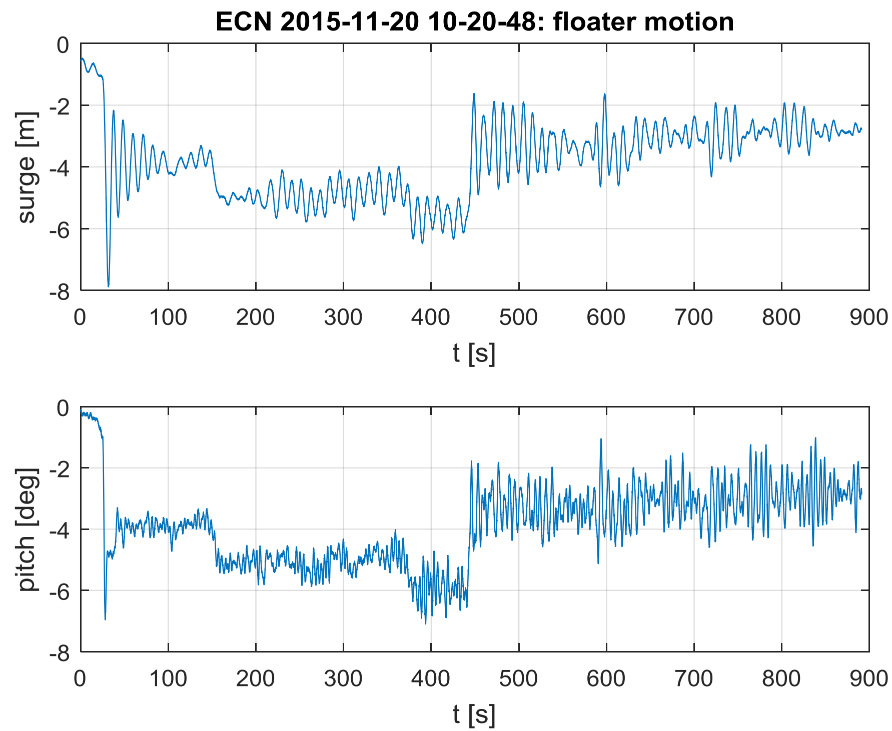




Model test results (3)

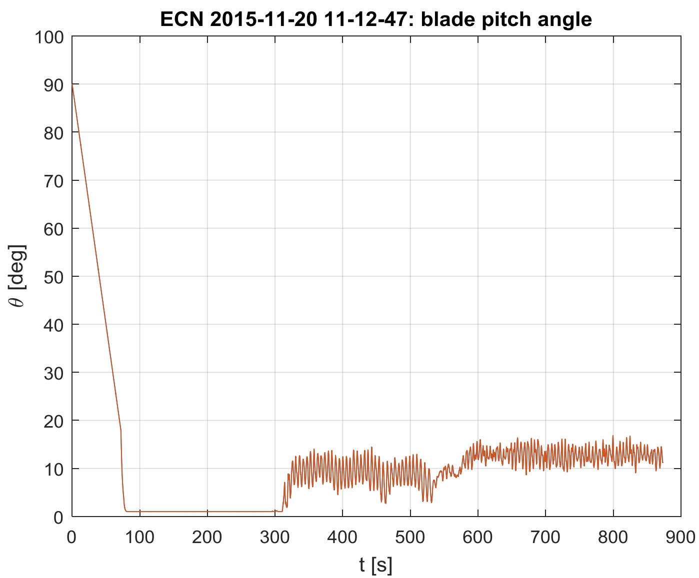
Staircase to verify:

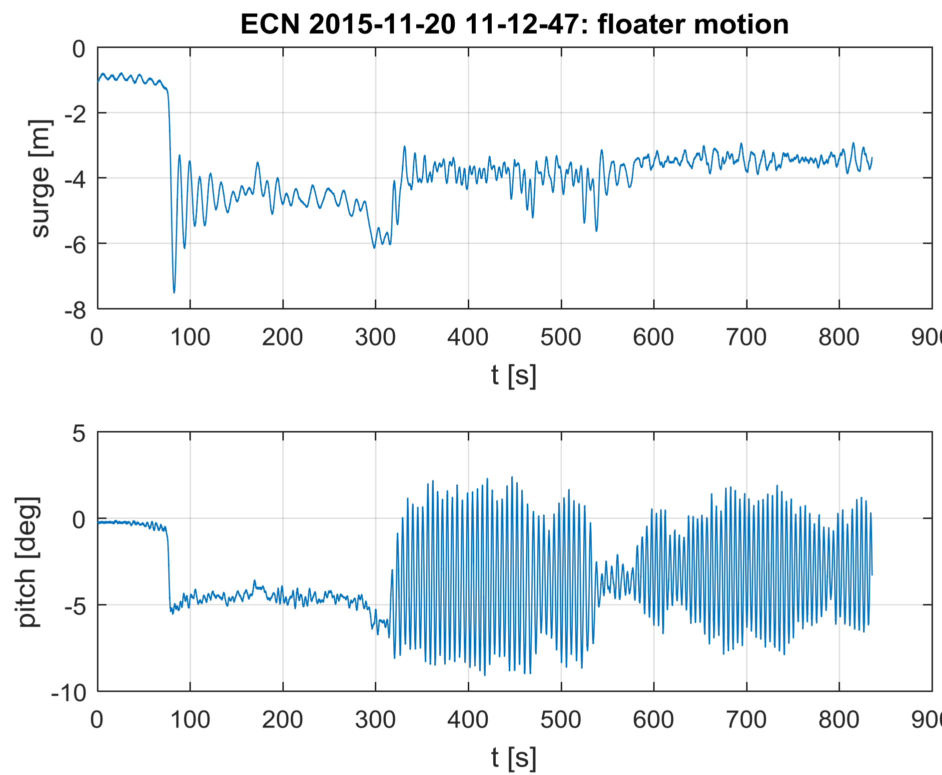
- Floater motions
- Tower top acceleration
- Floater motion observer



Model test results (4)

Limit cycling occurs with bottom-fixed controller!

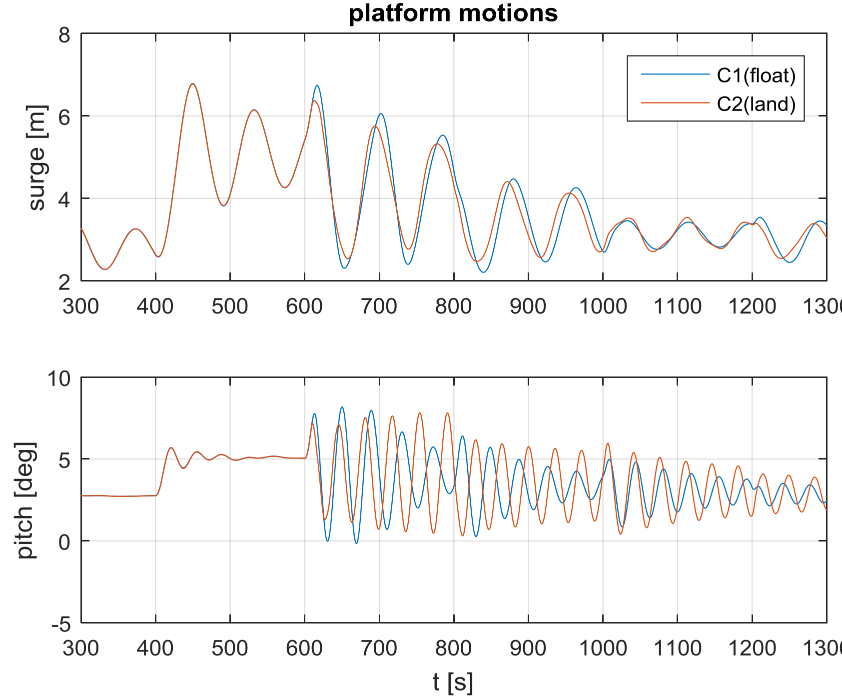




Model test results (5)

Decay test to see influence of different controllers:

- Detuning of the controller prevents limit cycling
- Damping can be increased by feedback of floater motions



Conclusion

Design of a controller for floating wind turbine model testing is feasible, given:

- Proper rotor characteristics
- Minor adjustments in the design (prevent early stall, gain scheduling etc)

This setup mimics full scale behavior of a floating wind turbine with controller.

The results from floating wind turbine model tests including control can be used to:

- Better calibrate the numerical models
- Evaluate the behavior and improve the design of the floating wind turbine and controller.

Thank you for your attention

ECN

This work has been carried out within the Dutch R&D project 'Floating Wind Energy' funded by the TO2 federation. Sebastien Gueydon, Haite van der Schaaf and Erik-Jan de Ridder from MARIN are acknowledged for the contribution.

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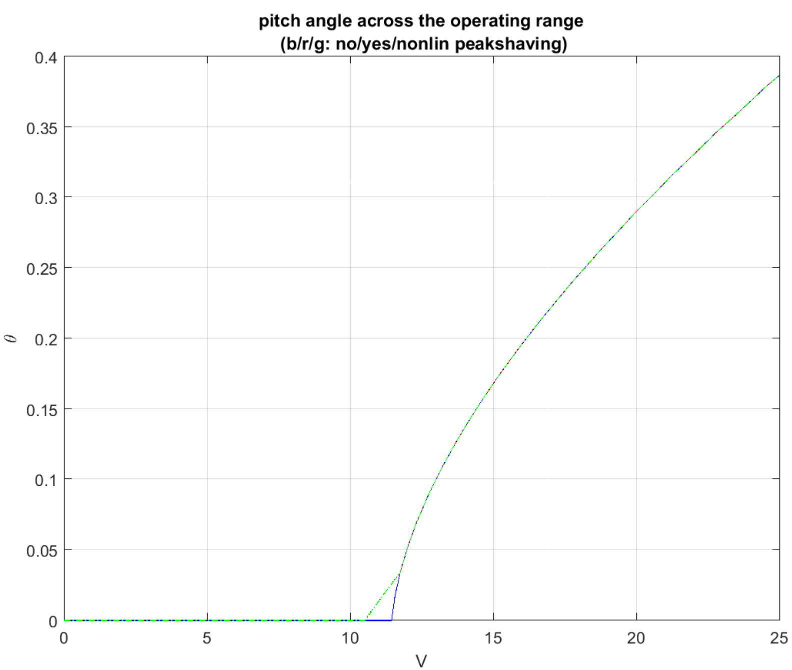
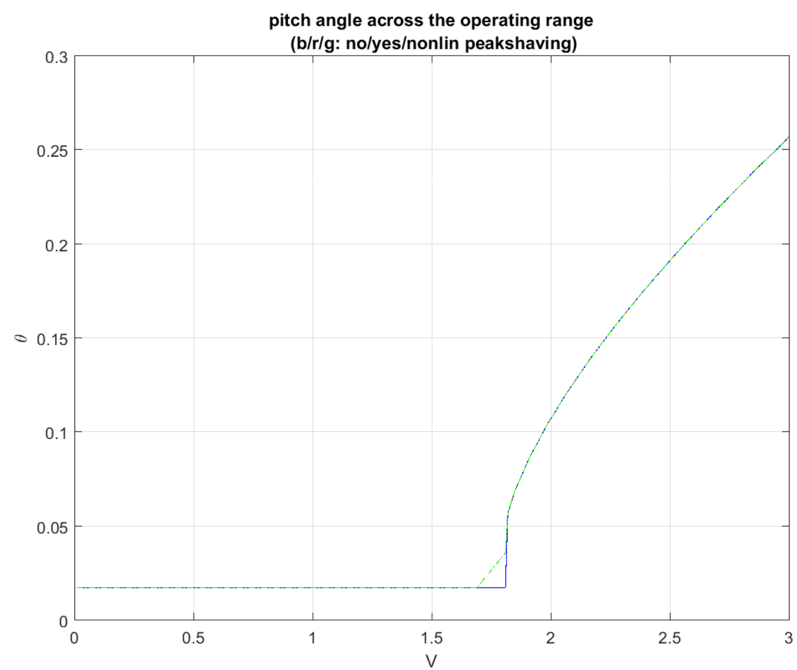
Control design at model scale

Full scale (OC4)

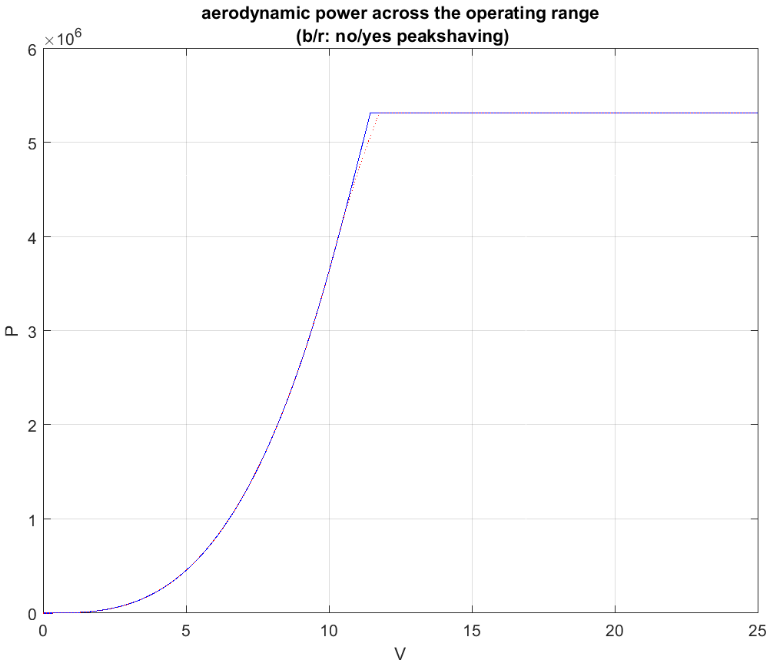


Model scale (OC5)

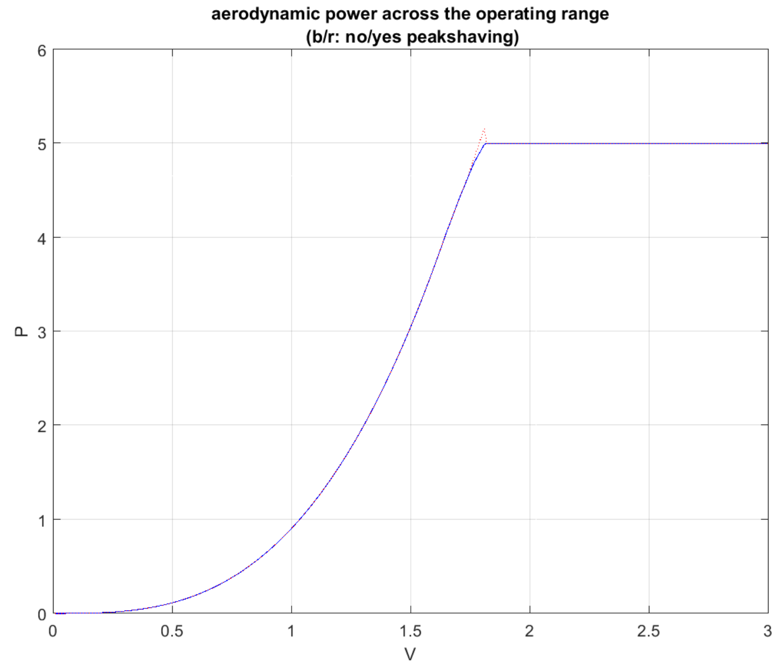


Control design at model scale

Full scale (OC4)

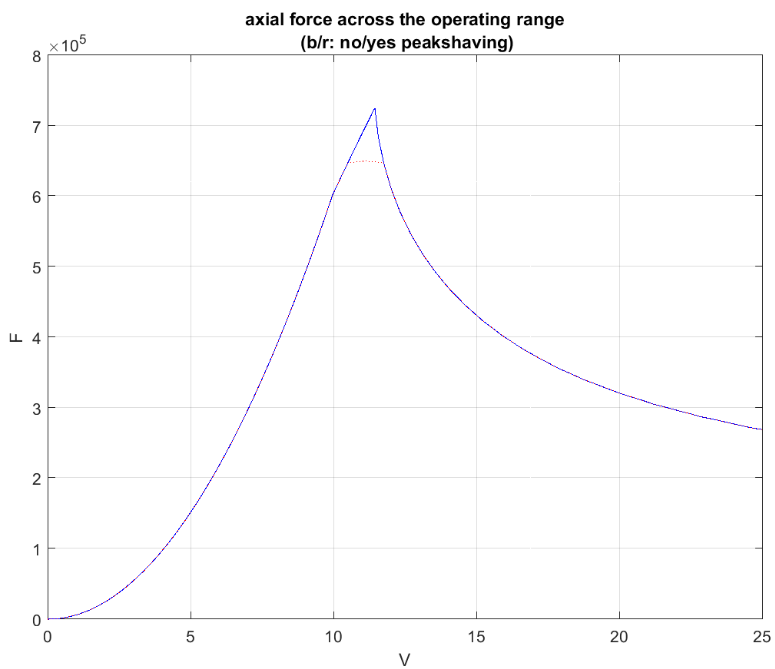


Model scale (OC5)

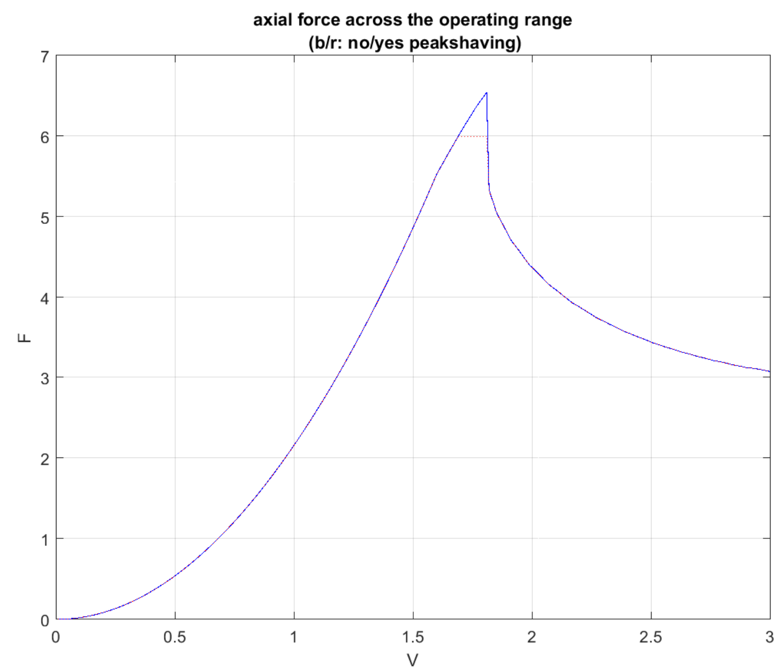


Control design at model scale

Full scale (OC4)



Model scale (OC5)



Control design at model scale

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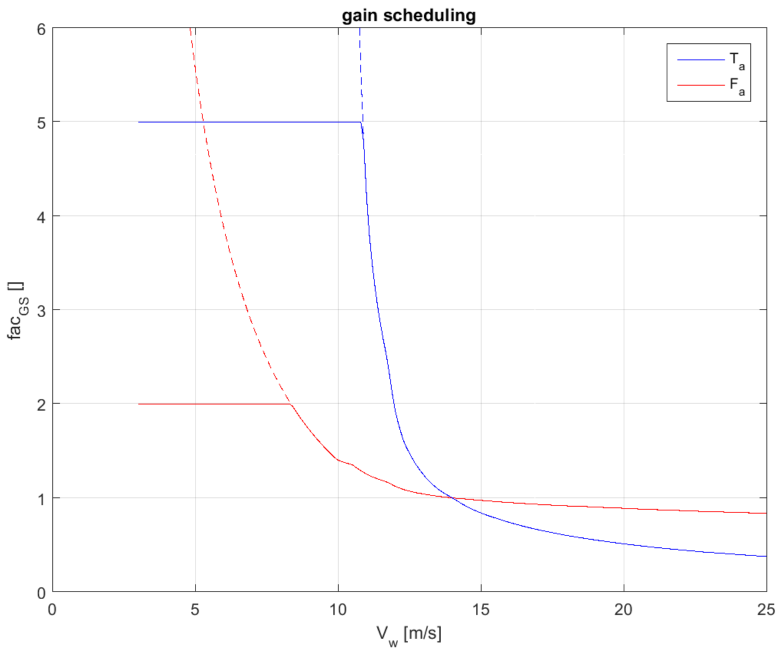

Model scale (OC5)