A control-oriented model for floating wind turbine stability and performance analysis

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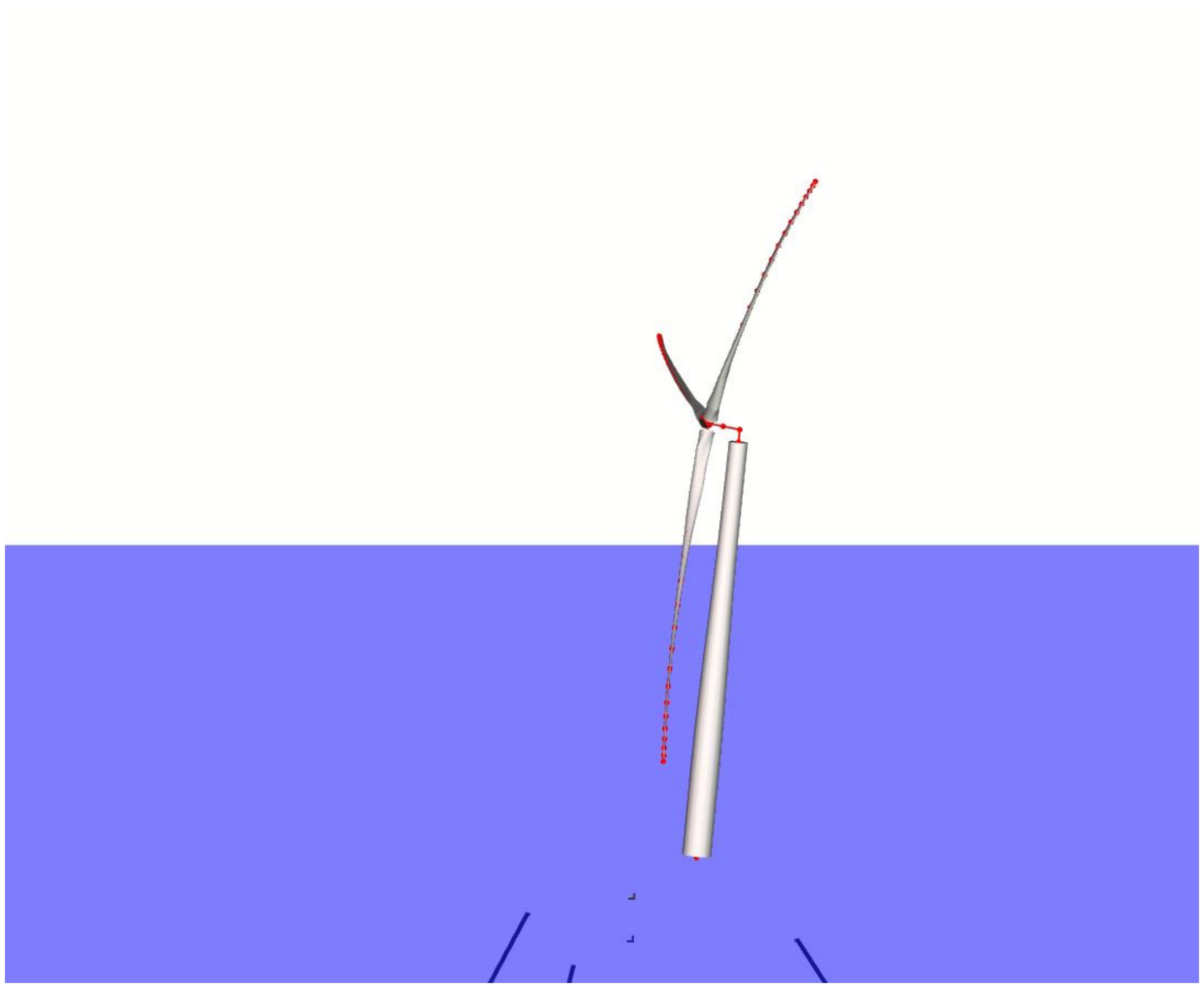
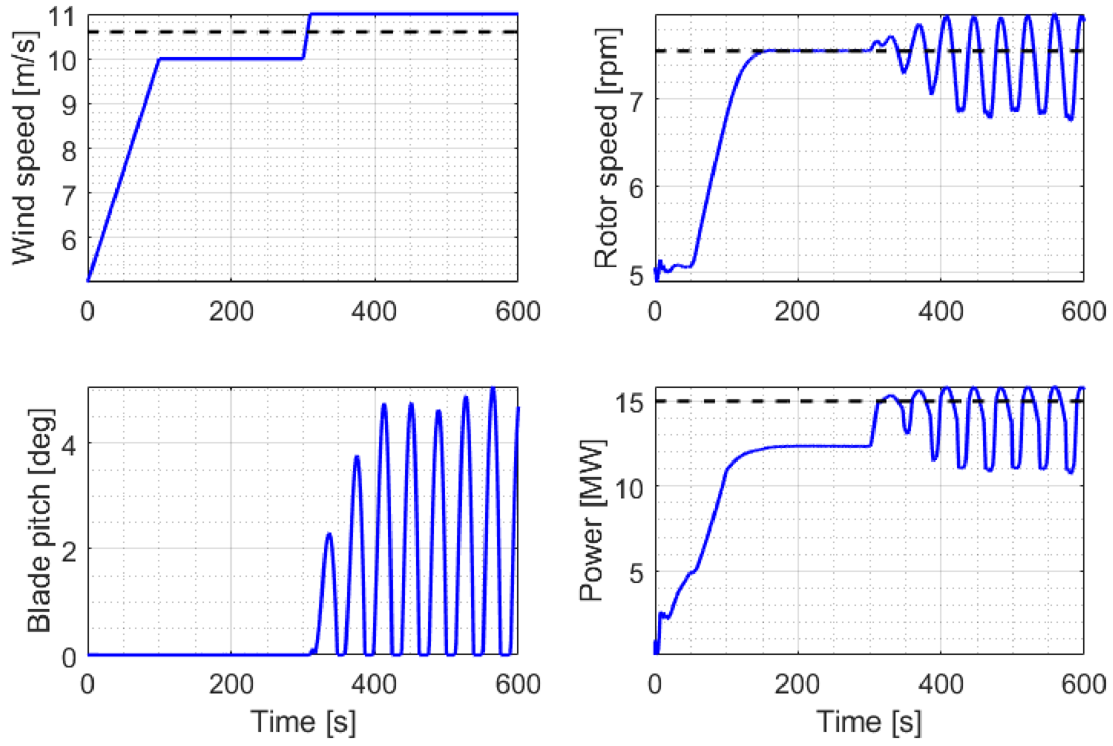
Problem: Floater pitch instability





Possible solutions

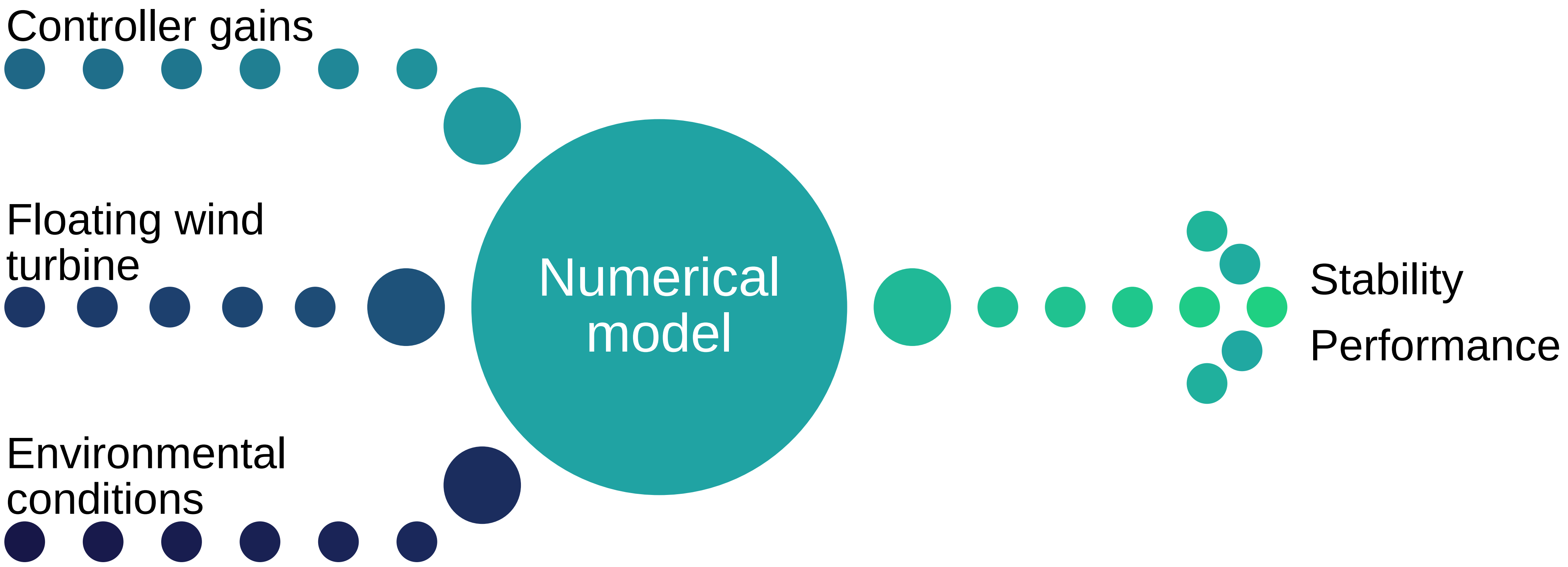
- **De-tuning the controller**
  - We make the controller ”slower” than the floater pitch motion
  - Simple solution, but the turbine gets worse at ”following the wind”

- **Nacelle-velocity control loops**
  - We include the nacelle velocity in a control feedback loop
    - Loop to blade pitch
    - Loop to generator torque
  - How to find the gains?

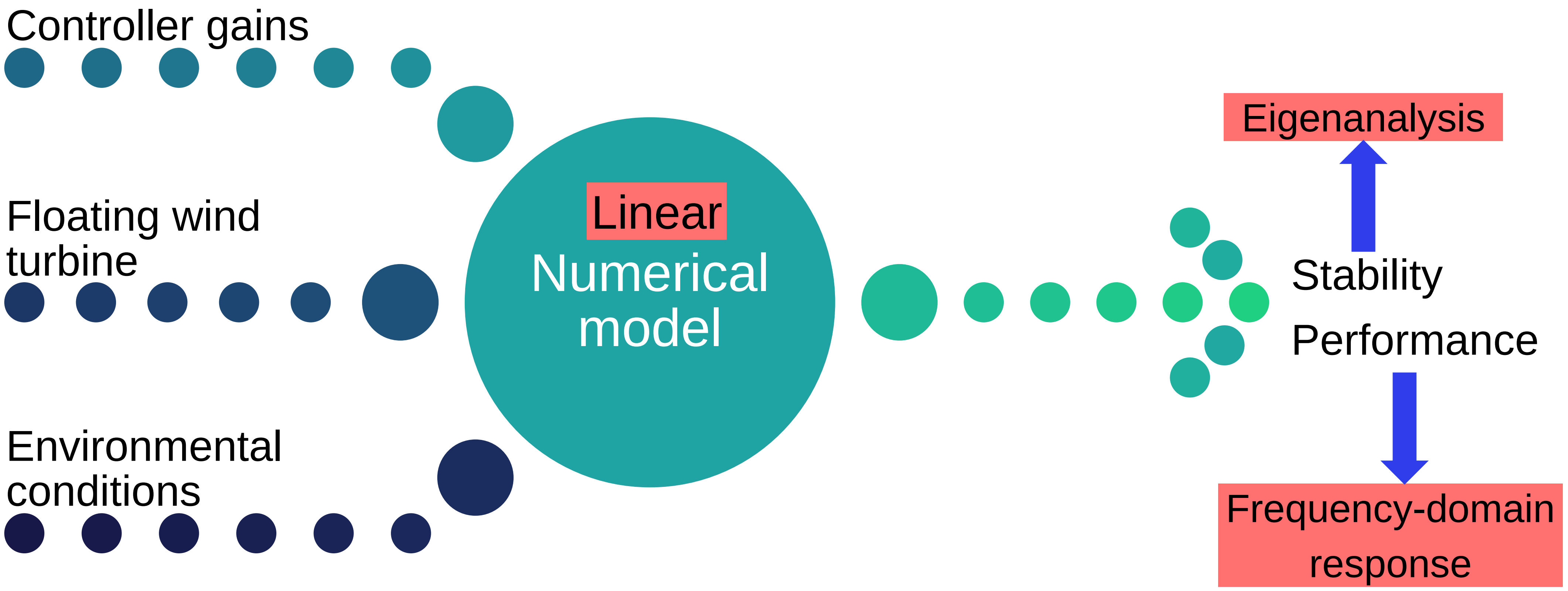
Further reading:

- Larsen and Hanson (2007), *A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine*. J. Phys.: Conf. Ser. 75 012073.
- Jonkman (2008), *Influence of control on the pitch damping of a floating wind turbine*. NREL/CP-500-42589, National Renewable Energy Laboratory.
- Yu et al (2018), *Evaluation of control methods for floating offshore wind turbines*. J. Phys.: Conf. Ser. 1104 012033.
- Lenfest et al (2020), *Tuning of nacelle feedback gains for floating wind turbine controllers using a two-dof model*. Proceedings of the ASME 39th International Conference on Ocean, Offshore and Arctic Engineering.
- Zhang (2021), *Control design and validation for floating wind turbines*. MSc report M-0472, DTU Wind Energy.

How to find the gains?



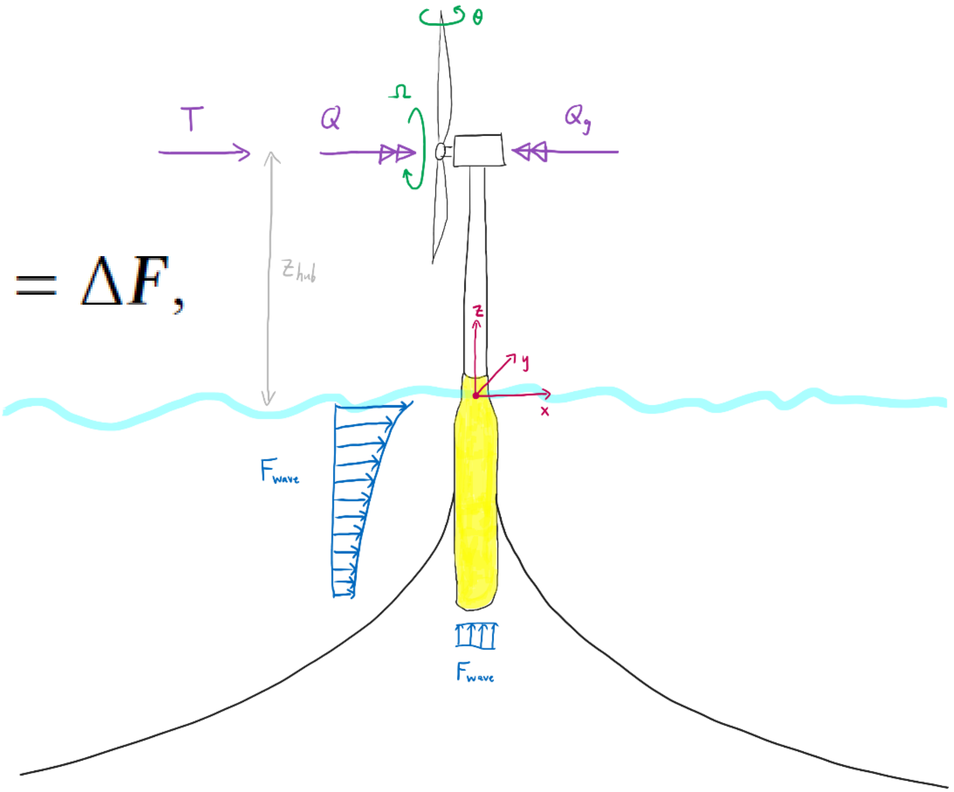
How to find the gains?



Floater motion

- Governed by 6x6 system of equations

$$(M + A)\ddot{\xi} + B\dot{\xi} + C\Delta\xi = \Delta F,$$



with:

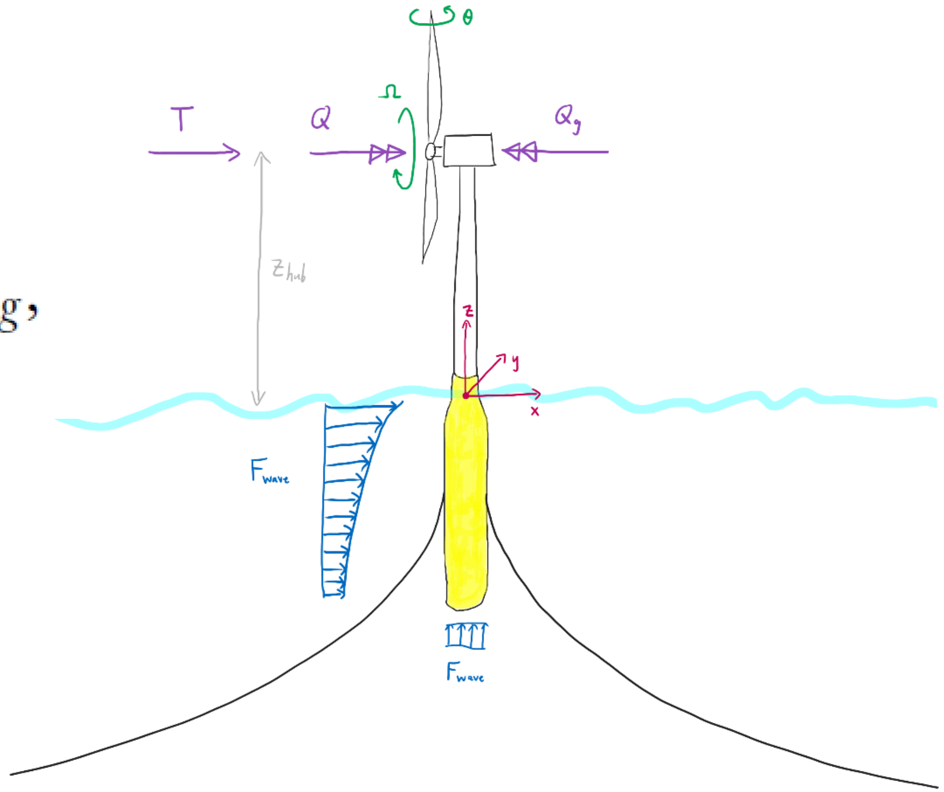
- Mass matrix
- Added mass matrix
- Damping matrix (hydrodynamic)
- Stiffness matrix (hydrostatic + mooring)

- All variables refer to the deviation from the steady-state

Drivetrain motion

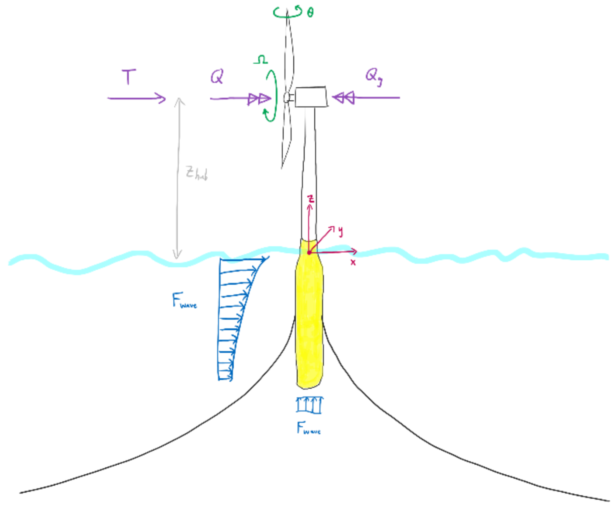
- Governed by

$$I_{dt}\frac{d\Omega}{dt} = Q - \frac{1}{\eta}Q_g,$$



with:

- Drivetrain inertia
- Rotor speed
- Aerodynamic torque
- Generator torque
- Generator efficiency



Coupling all together

- Fore-aft nacelle velocity

$$\dot{x}_{hub} = \dot{\xi}_1 + z_{hub}\dot{\xi}_5.$$

- Perturbation in wind speed

$$\Delta V = V - V_{op} = V_{turb} - \dot{x}_{hub} = V_{turb} - \left(\dot{\xi}_1 + z_{hub}\dot{\xi}_5\right).$$

- Deviation in blade pitch

$$\Delta\theta = \theta - \theta_{op} = k_p\dot{\phi} + k_i\phi + k_b\dot{x}_{hub} = k_p\dot{\phi} + k_i\phi + k_b\left(\dot{\xi}_1 + z_{hub}\dot{\xi}_5\right)$$

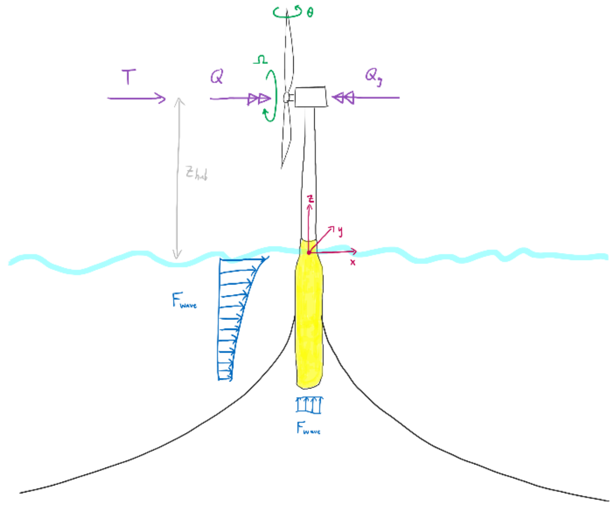
Error in rotor speed

Proportional

Integral

Nacelle-velocity to blade-pitch loop

Coupling all together



- The aerodynamic torque becomes

The aerodynamic thrust is linearized in a similar way →

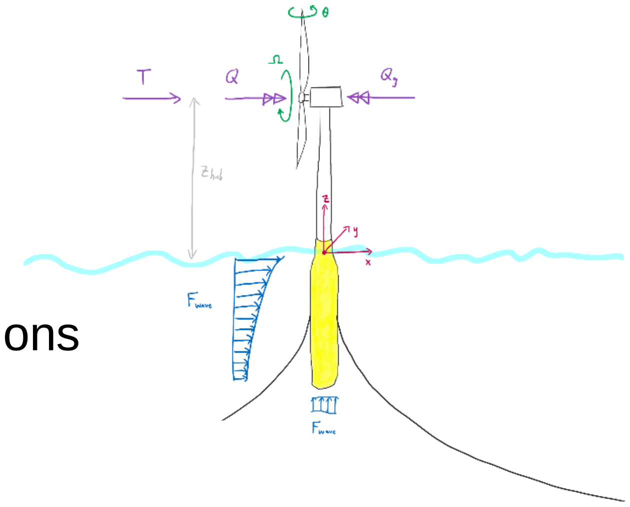
$$Q \approx Q_{op} + \frac{\partial Q}{\partial V}\Delta V + \frac{\partial Q}{\partial \Omega}\dot{\phi} + \frac{\partial Q}{\partial \theta}\Delta\theta.$$

$$Q \approx Q_{op} + \frac{\partial Q}{\partial V}V_{turb} + \left(\frac{\partial Q}{\partial \Omega} + \frac{\partial Q}{\partial \theta}k_p\right)\dot{\phi} + \frac{\partial Q}{\partial \theta}k_i\phi + \left(\frac{\partial Q}{\partial \theta}k_b - \frac{\partial Q}{\partial V}\right)\left(\dot{\xi}_1 + z_{hub}\dot{\xi}_5\right).$$

- The generator torque becomes

$$Q_g \approx Q_{g,op} + \frac{\partial Q_g}{\partial \Omega}\dot{\phi} - k_q\dot{x}_{hub} = Q_{g,op} + \frac{\partial Q_g}{\partial \Omega}\dot{\phi} - \boxed{k_q\left(\dot{\xi}_1 + z_{hub}\dot{\xi}_5\right)},$$

Nacelle-velocity to generator-torque loop

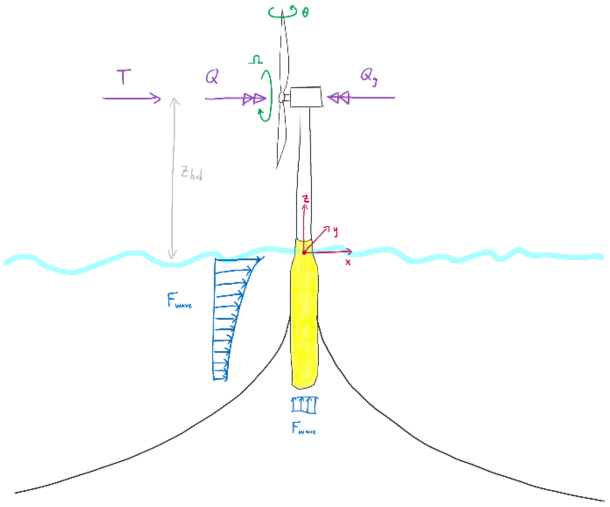


Coupling all together

- Motion-dependent terms are moved to the left-hand side as contributions to mass, damping or stiffness matrices

$$(\boldsymbol{M}+\boldsymbol{A})\begin{bmatrix}\ddot{\xi}_1\\ \ddot{\xi}_2\\ \ddot{\xi}_3\\ \ddot{\xi}_4\\ \ddot{\xi}_5\\ \ddot{\xi}_6\\ \ddot{\phi}\end{bmatrix}+\boldsymbol{B}\begin{bmatrix}\dot{\xi}_1\\ \dot{\xi}_2\\ \dot{\xi}_3\\ \dot{\xi}_4\\ \dot{\xi}_5\\ \dot{\xi}_6\\ \dot{\phi}\end{bmatrix}+\boldsymbol{C}\begin{bmatrix}\Delta\xi_1\\ \Delta\xi_2\\ \Delta\xi_3\\ \Delta\xi_4\\ \Delta\xi_5\\ \Delta\xi_6\\ \phi\end{bmatrix}=\begin{bmatrix}\frac{\partial T}{\partial V}V_{turb}\\ 0\\ 0\\ 0\\ \frac{\partial T}{\partial V}z_{hub}V_{turb}\\ 0\\ \frac{\partial Q}{\partial V}V_{turb}\end{bmatrix}+\boldsymbol{F}_{wave}.$$

Coupling all together



- Aero-servo-elastic contributions to mass ($\boldsymbol{M}$), damping ($\boldsymbol{B}$) and stiffness ($\boldsymbol{C}$) matrices

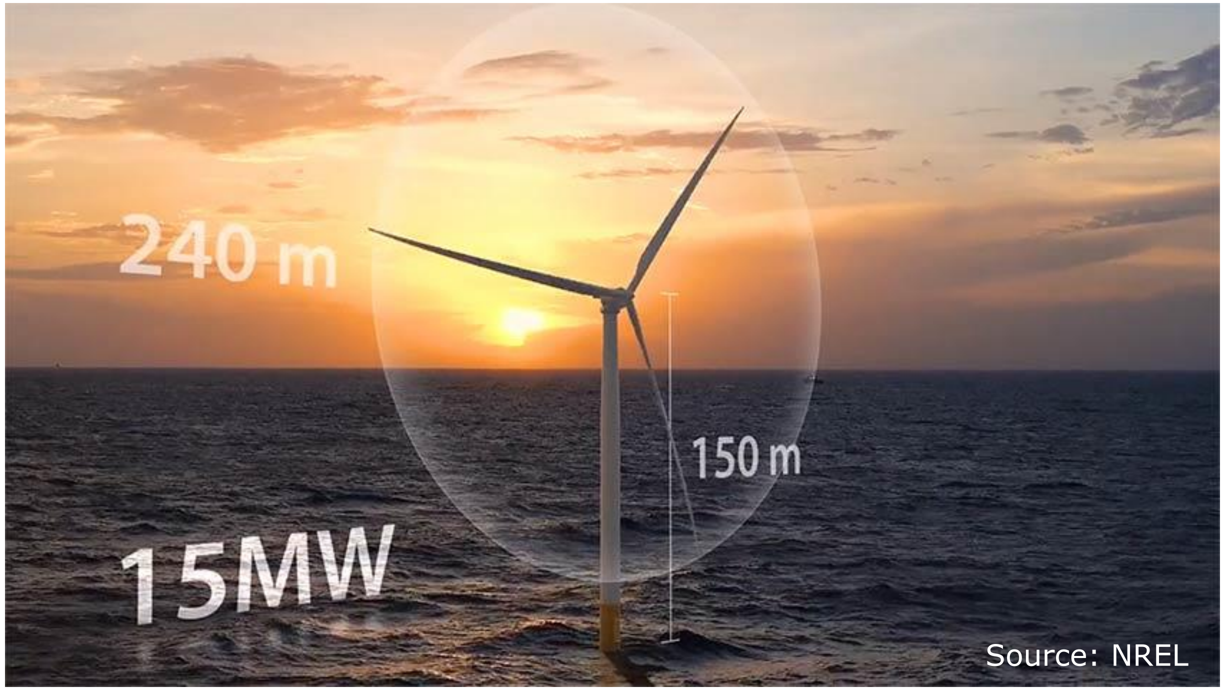
$$C_{ase} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & -\frac{\partial T}{\partial \theta} k_i \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{\partial T}{\partial \theta} k_i z_{hub} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{\partial Q}{\partial \theta} k_i \end{bmatrix}$$

$$M_{ase} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_{dt} \end{bmatrix}$$

$$B_{ase} = \begin{bmatrix} \frac{\partial T}{\partial V} - \frac{\partial T}{\partial \theta} k_b & 0 & 0 & 0 & \left(\frac{\partial T}{\partial V} - \frac{\partial T}{\partial \theta} k_b\right) z_{hub} & 0 & -\frac{\partial T}{\partial \Omega} - \frac{\partial T}{\partial \theta} k_p \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \left(\frac{\partial T}{\partial V} - \frac{\partial T}{\partial \theta} k_b\right) z_{hub} & 0 & 0 & 0 & \left(\frac{\partial T}{\partial V} - \frac{\partial T}{\partial \theta} k_b\right) z_{hub}^2 & 0 & \left(-\frac{\partial T}{\partial \Omega} - \frac{\partial T}{\partial \theta} k_p\right) z_{hub} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{\partial Q}{\partial V} - \frac{1}{\eta} k_q - \frac{\partial Q}{\partial \theta} k_b & 0 & 0 & 0 & \left(\frac{\partial Q}{\partial V} - \frac{1}{\eta} k_q - \frac{\partial Q}{\partial \theta} k_b\right) z_{hub} & 0 & \frac{1}{\eta} \frac{\partial Q_g}{\partial \Omega} - \frac{\partial Q}{\partial \Omega} - \frac{\partial Q}{\partial \theta} k_p \end{bmatrix}$$

Our case study

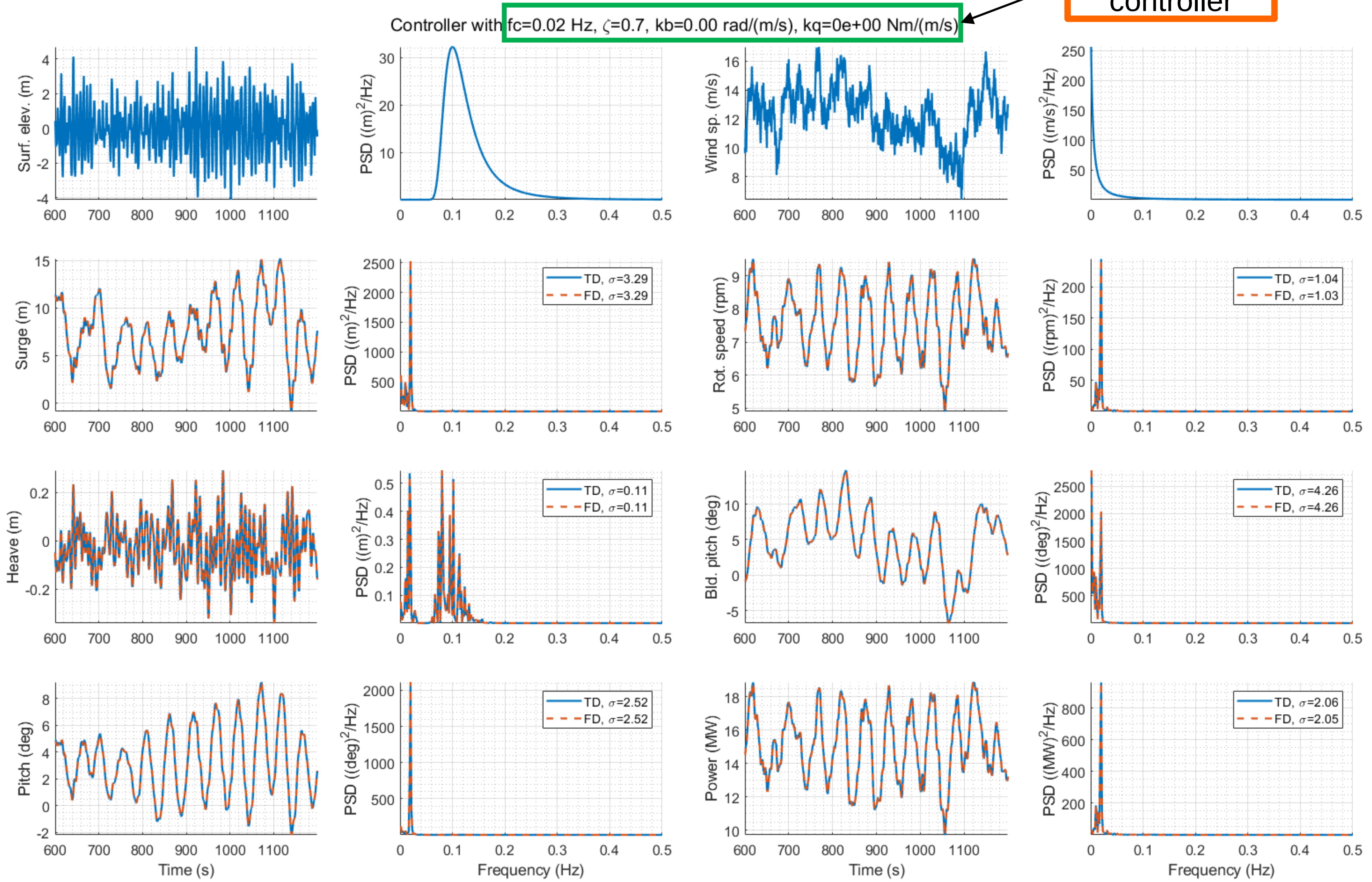
- IEA Wind 15 MW turbine



- WindCrete spar-buoy floater

Response to wind and waves

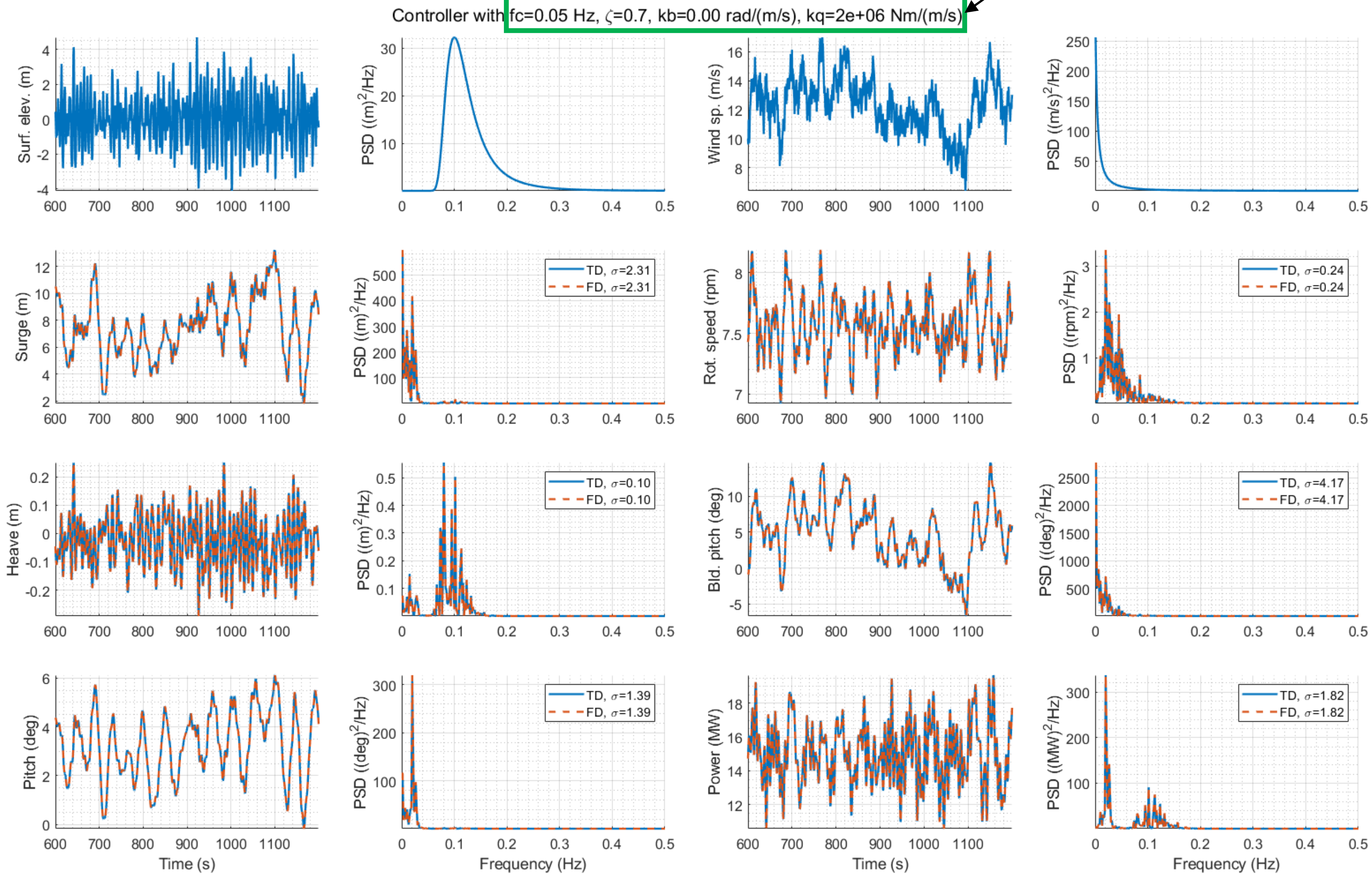
De-tuned controller



Pitch damping ratio 3.75%

Response to wind and waves

Nacelle-velocity feedback to generator torque active

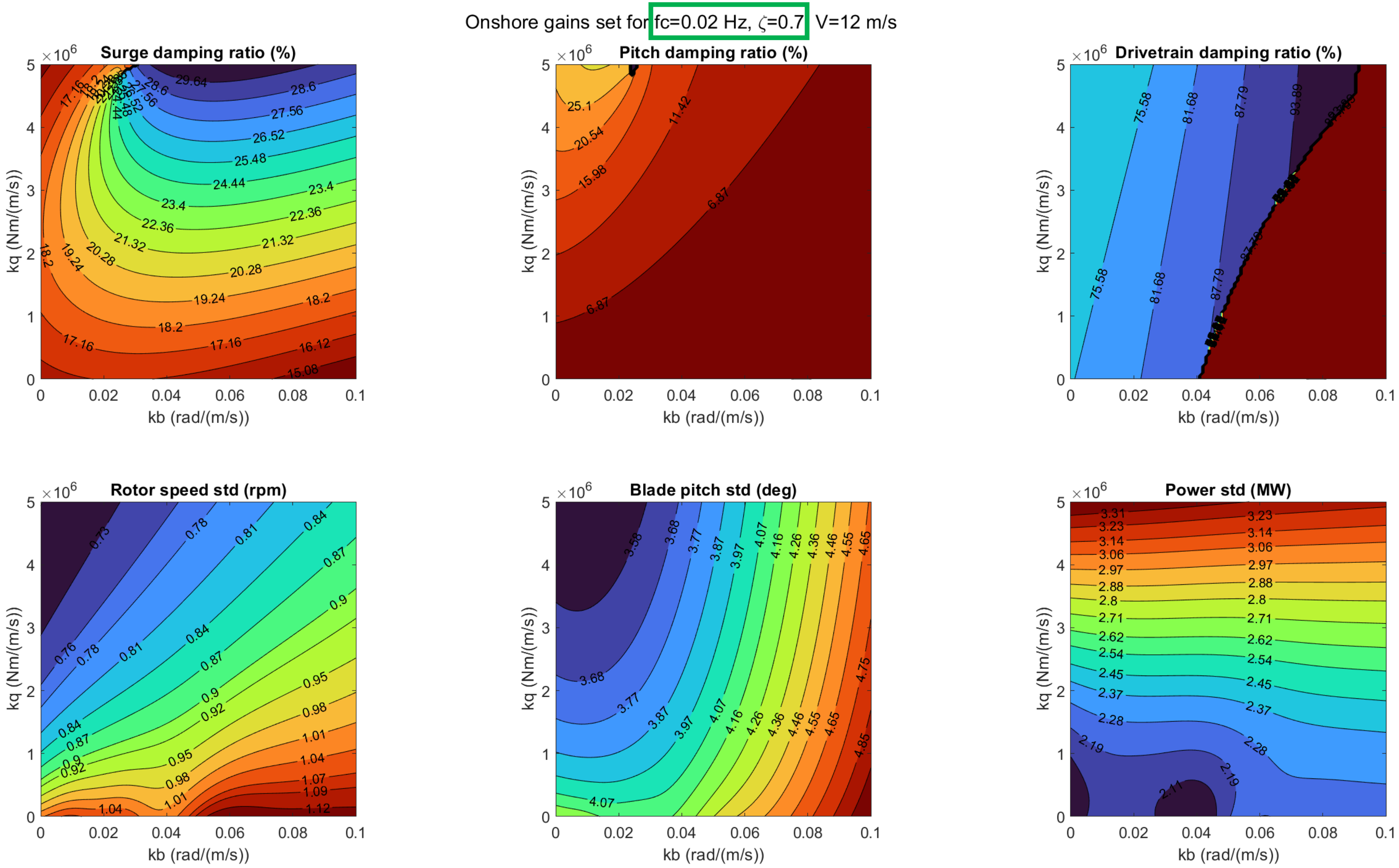


Pitch damping ratio 10.25%

Parametric study on 100x100 grid

Damping ratios (blue=larger) →

Standard deviations (blue=smaller) →



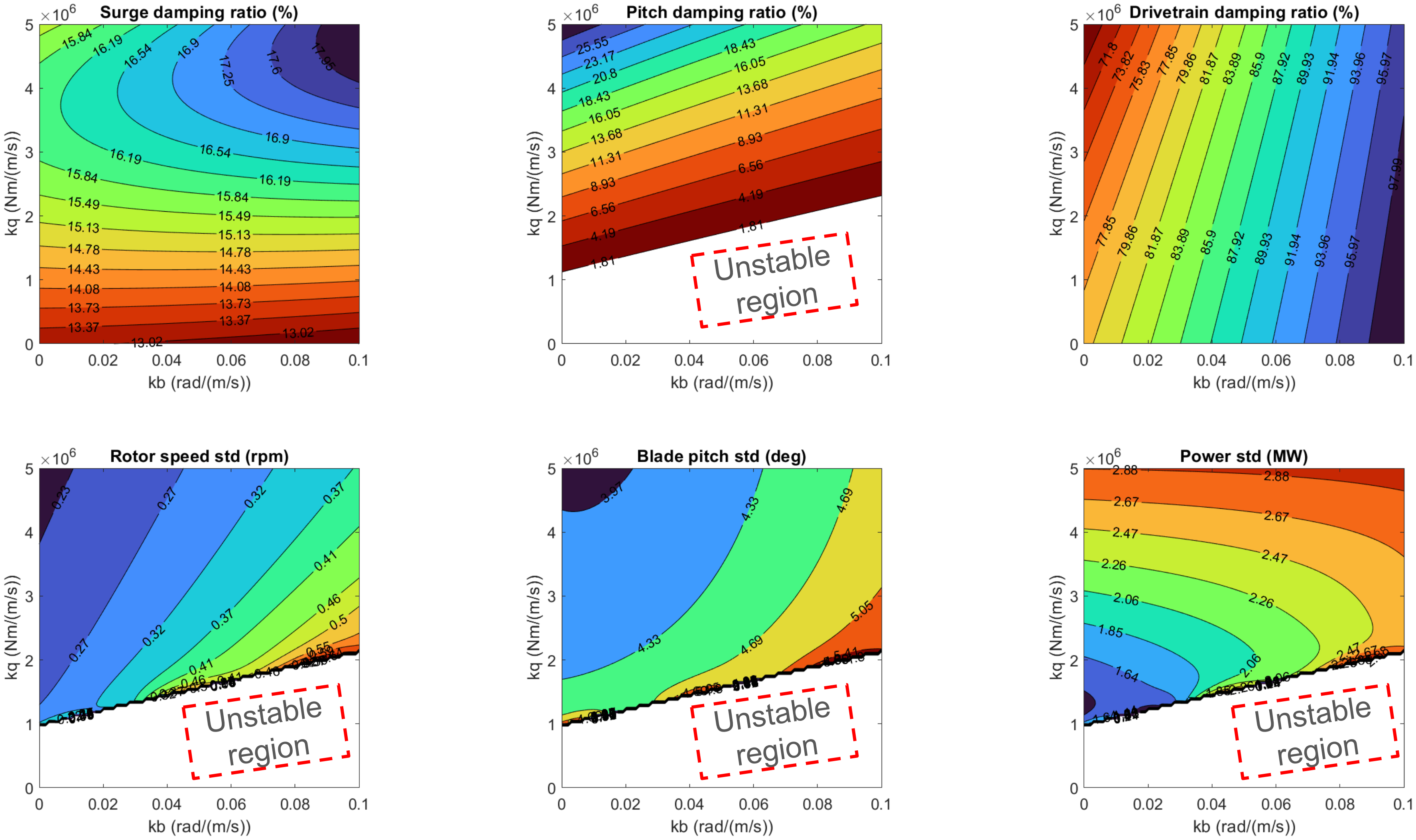
10.000 controllers in ~3 min

Parametric study on 100x100 grid

Onshore gains set for fc=0.05 Hz, ζ=0.7 V=12 m/s

Damping ratios (blue=larger)

Standard deviations (blue=smaller)



10.000 controllers in ~3 min

Conclusions

- Model to investigate controller stability and performance for floating wind turbines

- Classic PI gains + nacelle-velocity feedback gains
  – Blade pitch
  – Generator torque

- Efficient evaluation thanks to linear response formulation
  – 10.000 controllers in ~3 min

- Must be followed by analysis in time-domain model, including:
  – Realistic wind loads
  – Actuator dynamics
  – Nonlinear effects
  – etc

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