Floating wind turbine control

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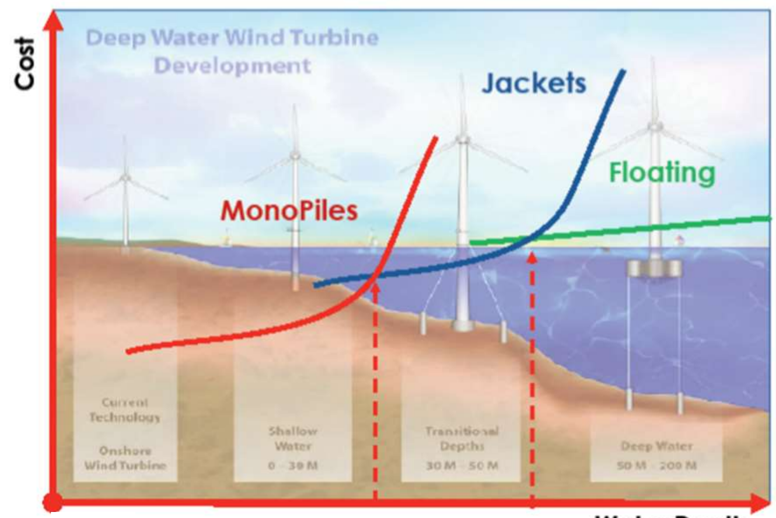
(based on the slides of ir. Gijs van der Veen)

Introduction

- Off-shore turbines:
  - Larger wind resource
  - Lower turbulence levels
  - Large areas available

- Floating off-shore turbines:
  - Most cost-effective solution when depth >50m
  - On-shore construction, serial production

- Technical challenges:
  - Safety
  - Modelling and simulation (loads)
  - Control system

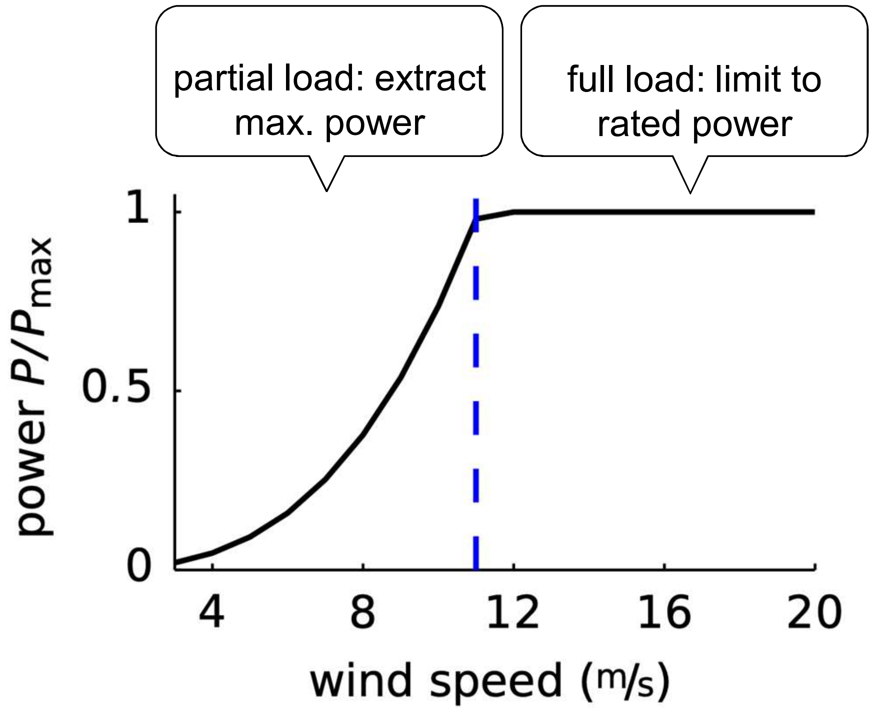


NREL

WindFloat (Principle Power USA)

Control challenges

⑩ In full load control: track rated (~maximum) power



Control challenges, full load

2. increase pitch angle

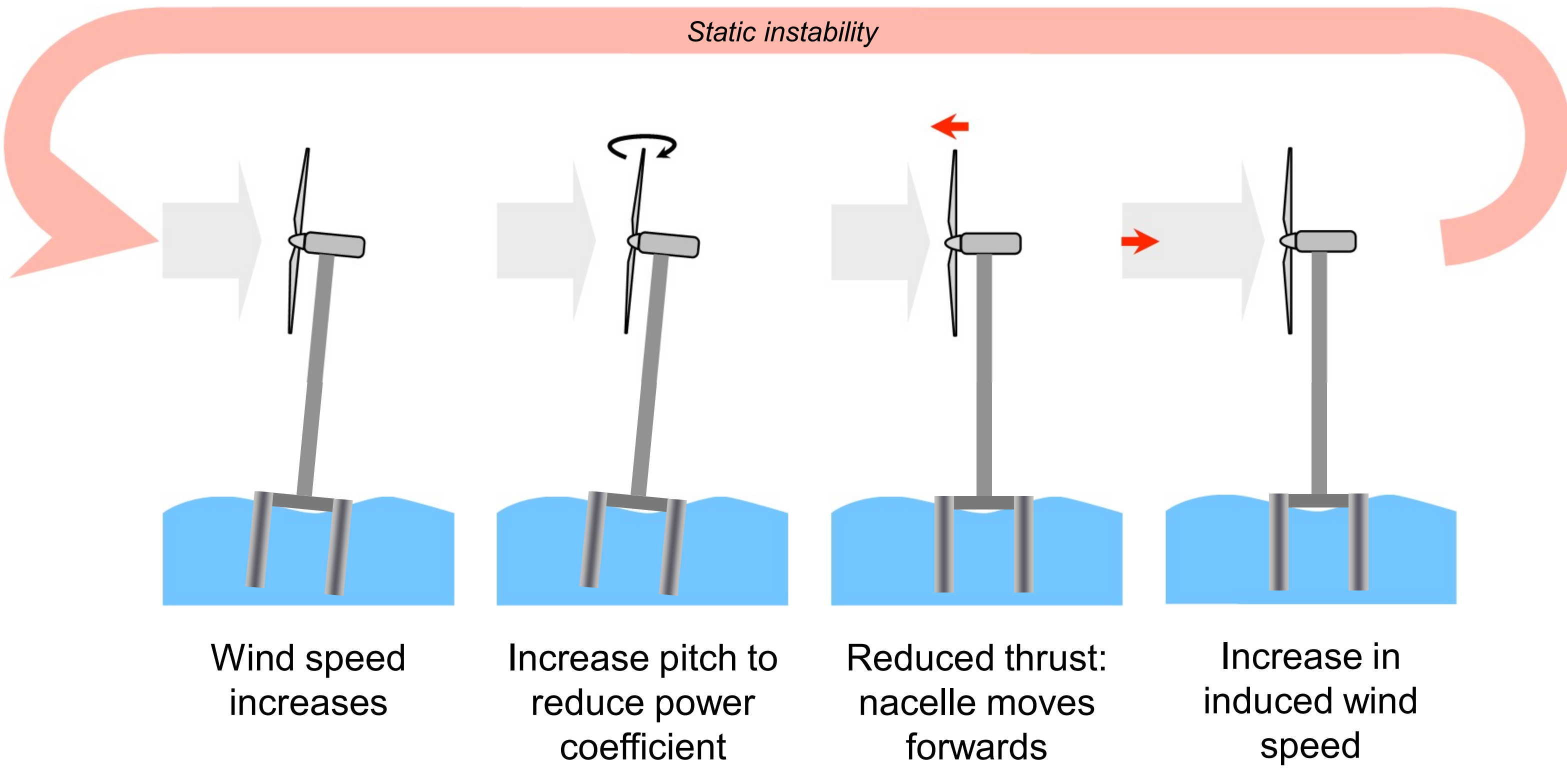
1. wind speed increases

$$P = \frac{1}{2}\rho\pi R^2 C_P(\lambda, \beta) V_\infty^3$$

Strict specifications:

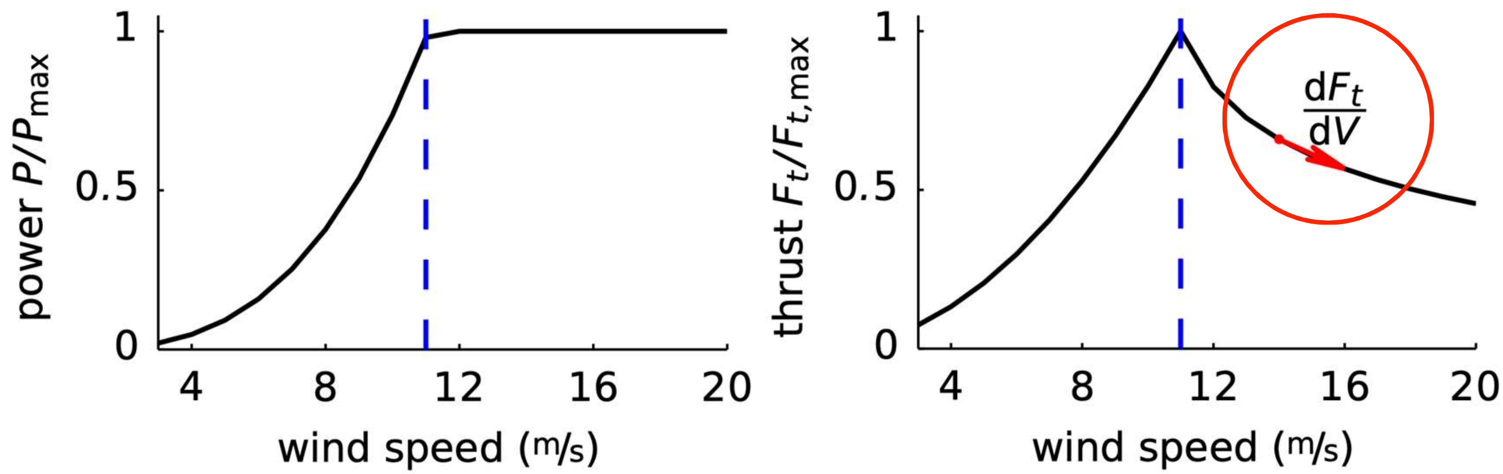
- Do not exceed generator speed limit → shutdown
- Do not exceed fore-aft tilt limits

Potential instability problem

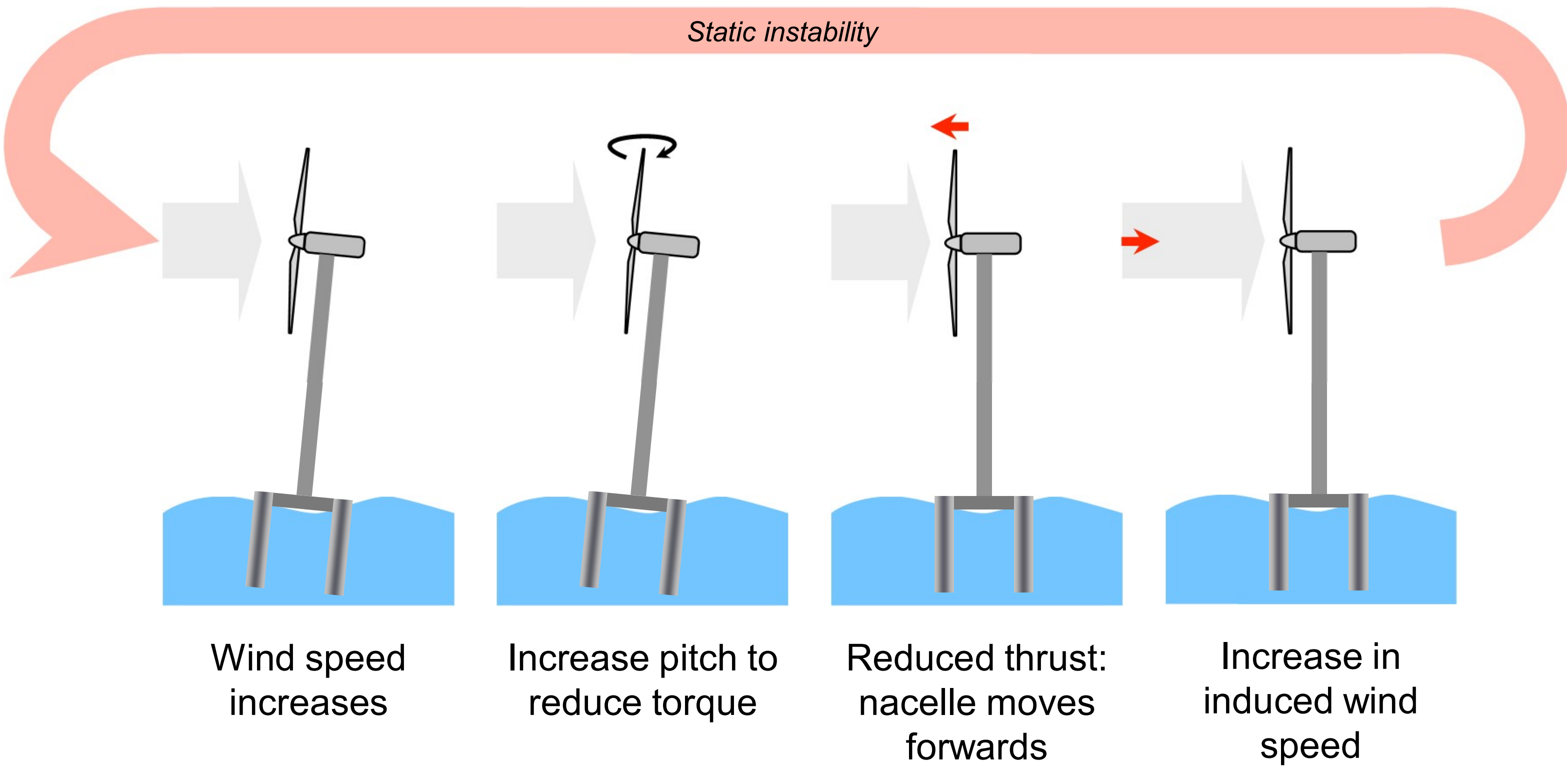


Potential instability problem

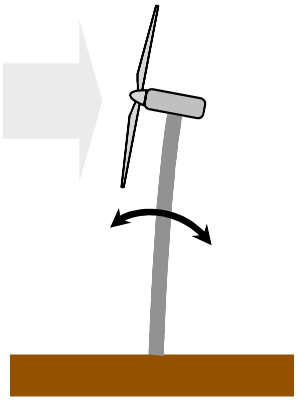
⑩ Also follows from steady-state thrust curve



Potential instability problem

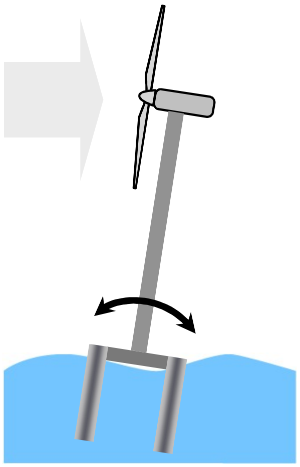


Fixed vs floating



⑩ Conventional turbines on fixed foundation:

- ~0.3 Hz bending mode
- Controller much slower than this



⑩ Floating turbines:

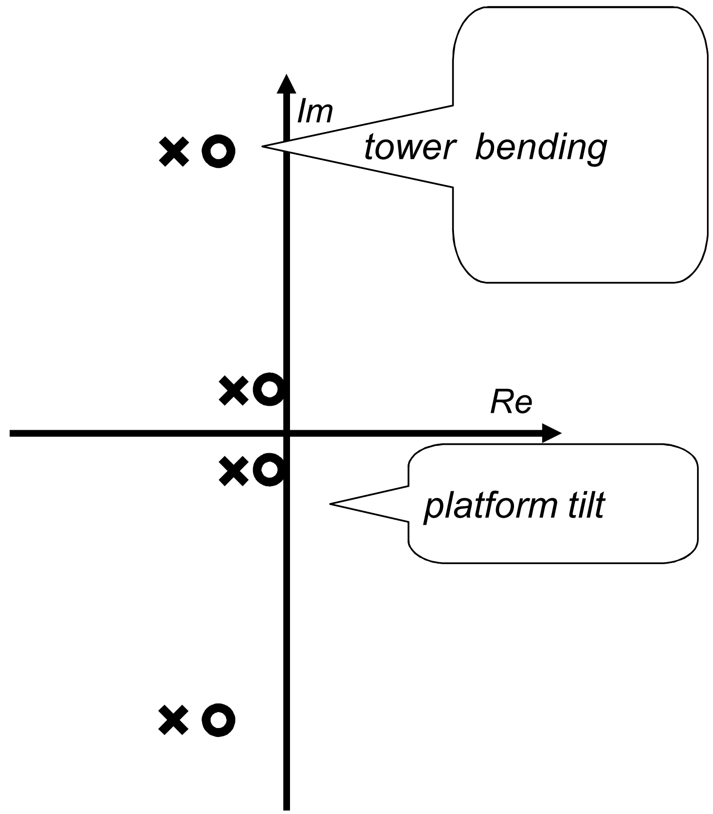
- ~0.03 Hz tilt mode
- Within controller bandwidth!
- Right-half-plane zeros

Simplified dynamic model

- Pitch to generator speed dynamics

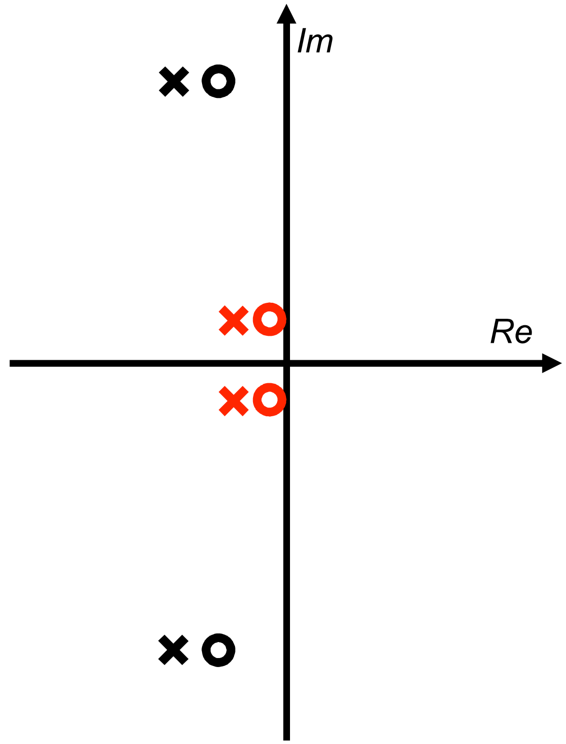
- Zero locations

$$z \approx -\frac{1}{2}\left(4\pi\zeta_{twr}f_{twr} + a_1\frac{dF_T}{dV}\right) \pm j2\pi f_{twr}$$



Simplified dynamic model

- Pitch to generator speed dynamics



- Zero locations

$$z \approx -\frac{1}{2}\left(4\pi\zeta_{\mathrm{twr}} f_{\mathrm{twr}} + a_1 \frac{\mathrm{d}F_{\mathrm{T}}}{\mathrm{d}V}\right) \pm j2\pi f_{\mathrm{twr}}$$

$$a_1 \frac{\mathrm{d}F_{\mathrm{T}}}{\mathrm{d}V} > -4\pi\zeta_{\mathrm{twr}} f_{\mathrm{twr}}$$

- Not a fundamental limitation, yet lightly damped oscillations in closed-loop

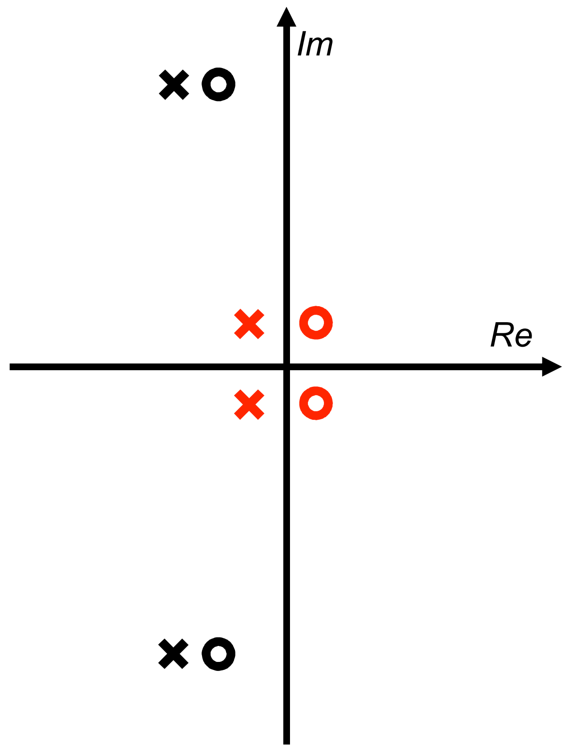
Simplified dynamic model

- Pitch to generator speed dynamics

- Zero locations

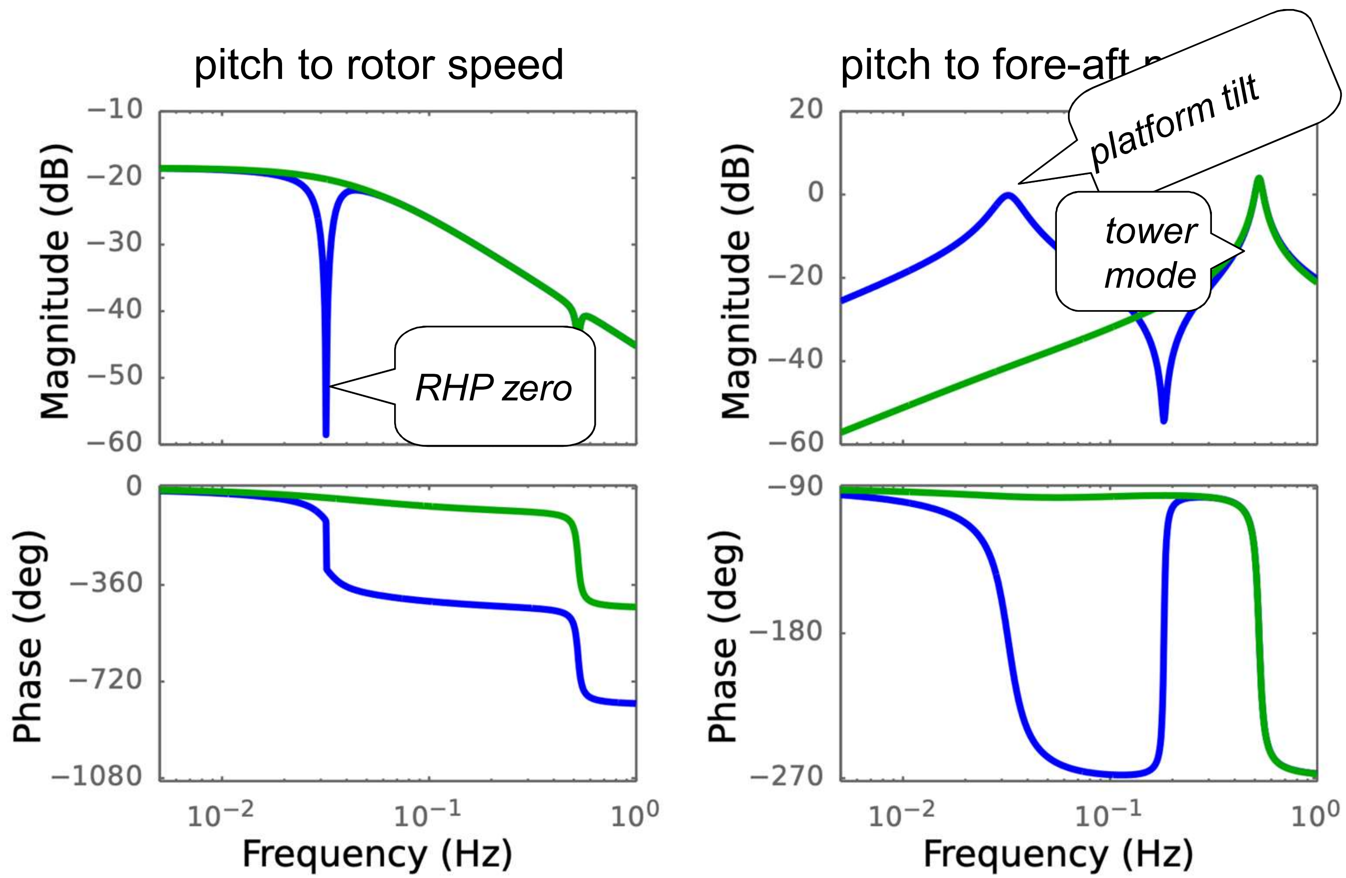
$$z \approx -\frac{1}{2}\left(4\pi\zeta_{\mathrm{twr}} f_{\mathrm{twr}} + a_1 \frac{\mathrm{d}F_{\mathrm{T}}}{\mathrm{d}V}\right) \pm j2\pi f_{\mathrm{twr}}$$

$$a_1 \frac{\mathrm{d}F_{\mathrm{T}}}{\mathrm{d}V} < -4\pi\zeta_{\mathrm{twr}} f_{\mathrm{twr}}$$



- Fundamental limitation

Frequency domain illustration



Potential solutions

1. Reduce controller bandwidth

2. Parallel compensation

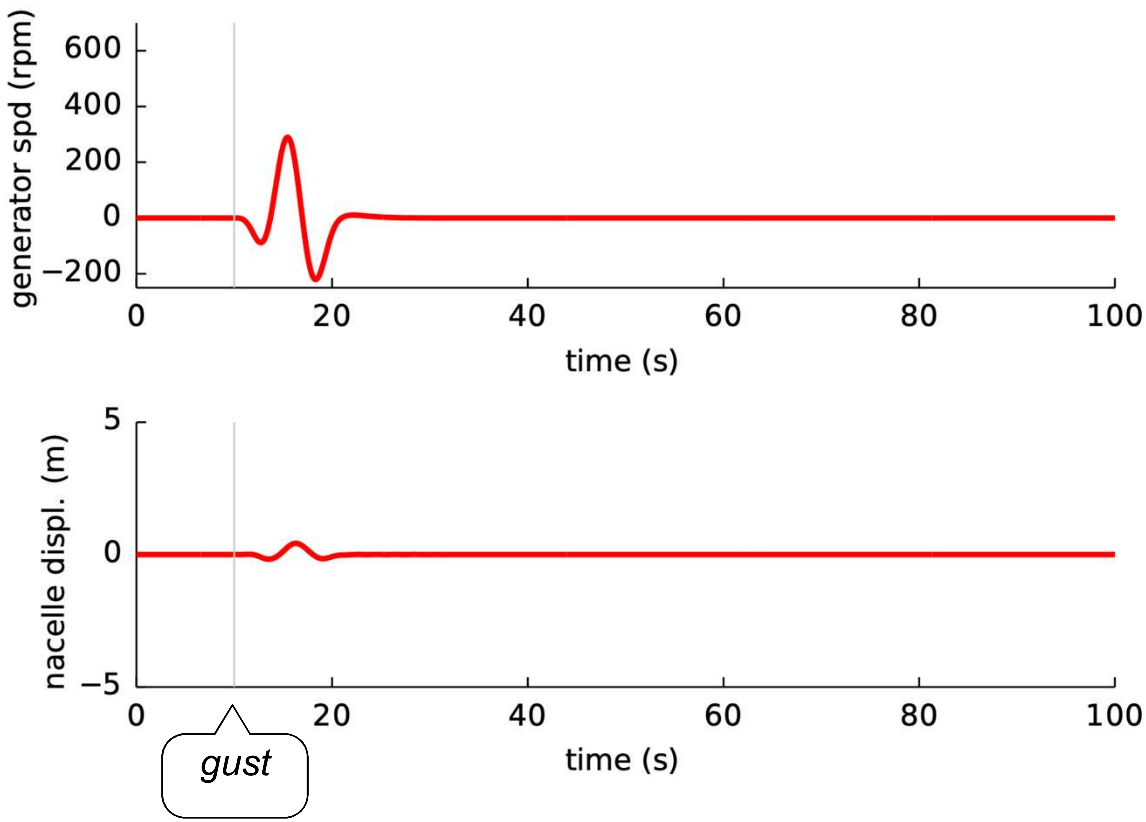
3. Add control DOF

4. Pitch-to-stall operation

1. Reduce controller bandwidth [1]

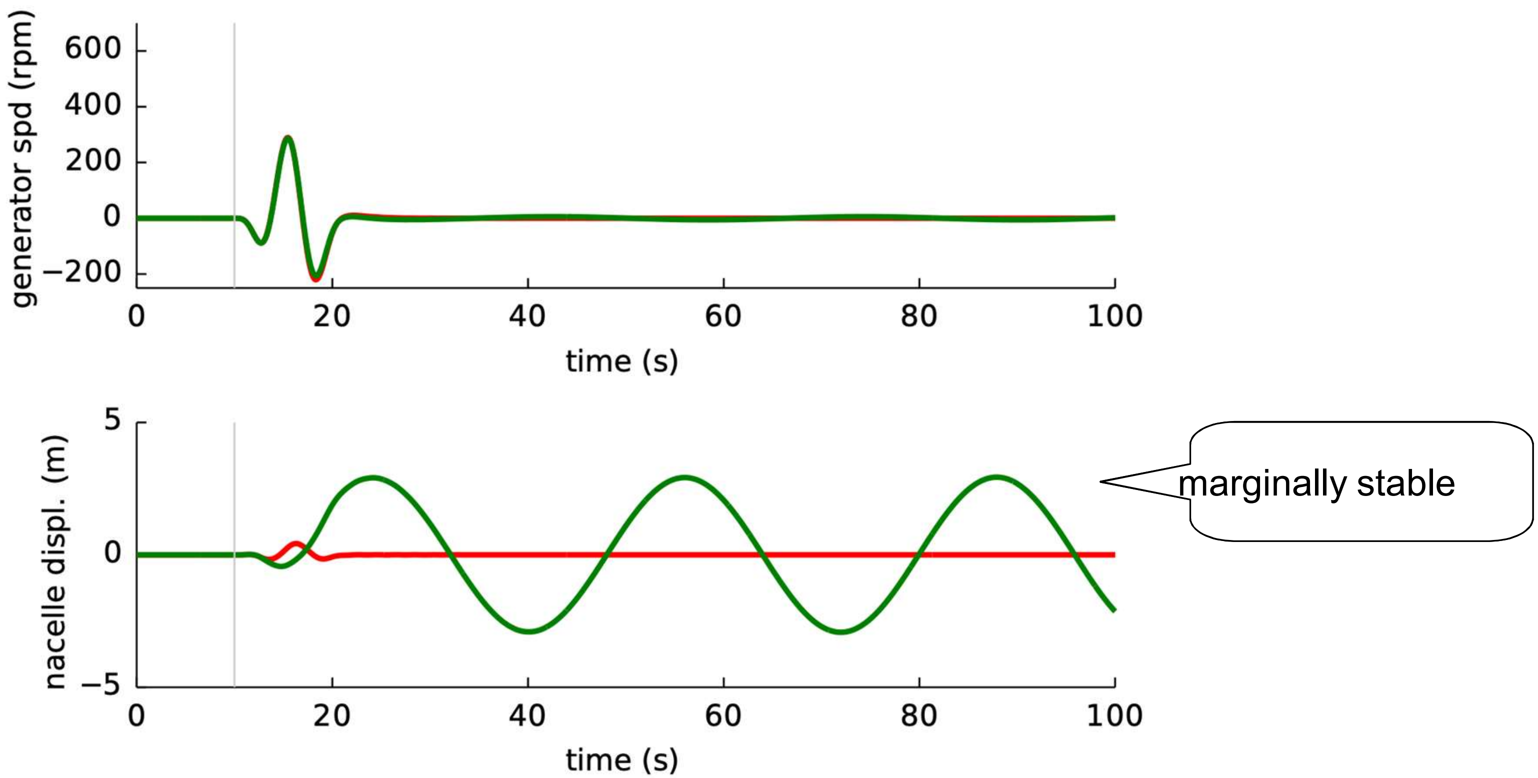
[1] J. Jonkman

⑩ Fixed turbine with conventional PI controller - bandwidth 0.2 Hz



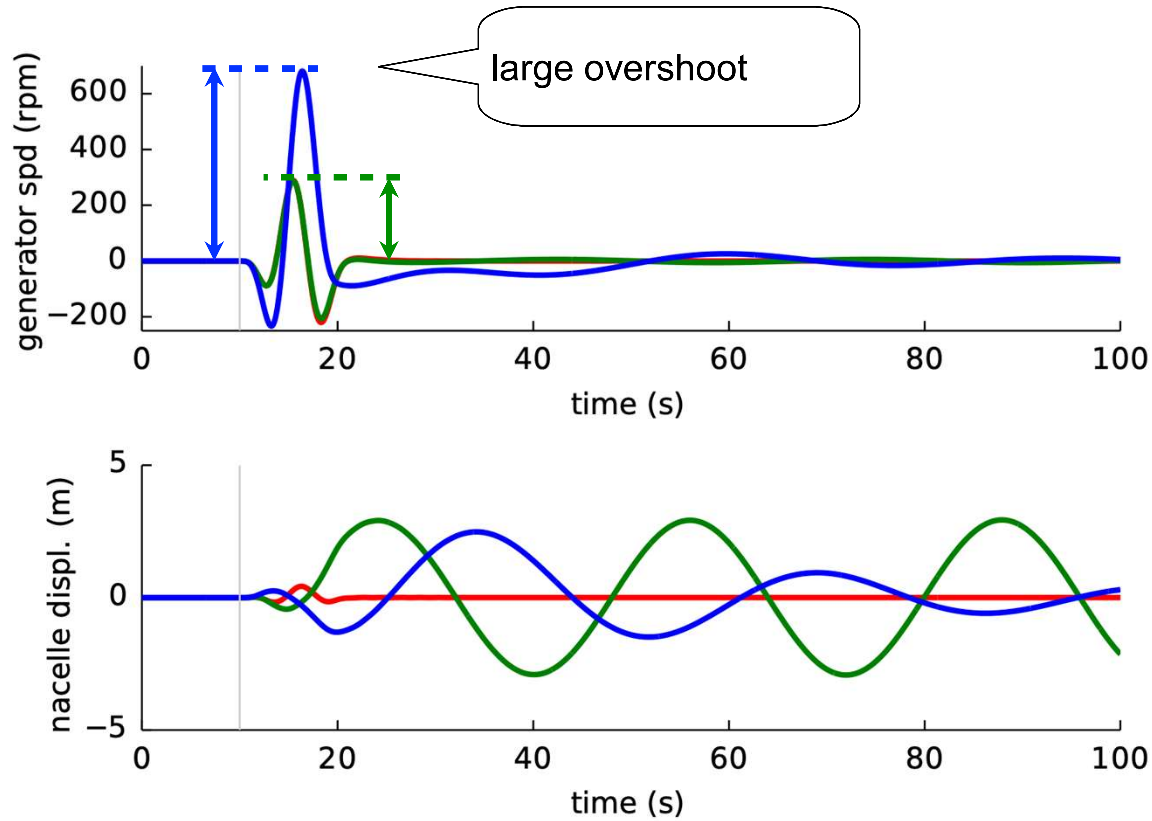
1. Reduce controller bandwidth

⑩ Floating turbine with conventional PI controller - bandwidth 0.2 Hz



1. Reduce controller bandwidth

⑩ Floating turbine with detuned PI controller - bandwidth 0.02 Hz



1. Reduce controller bandwidth - summary

- Reduce bandwidth due to RHP zeros
- Larger speed excursions
  - Either: premature shutdowns due to generator over-speed
  - Or: choose lower speed/power set-point
- Accept larger power fluctuations and poor tilt damping

Potential solutions

1. Reduce controller bandwidth

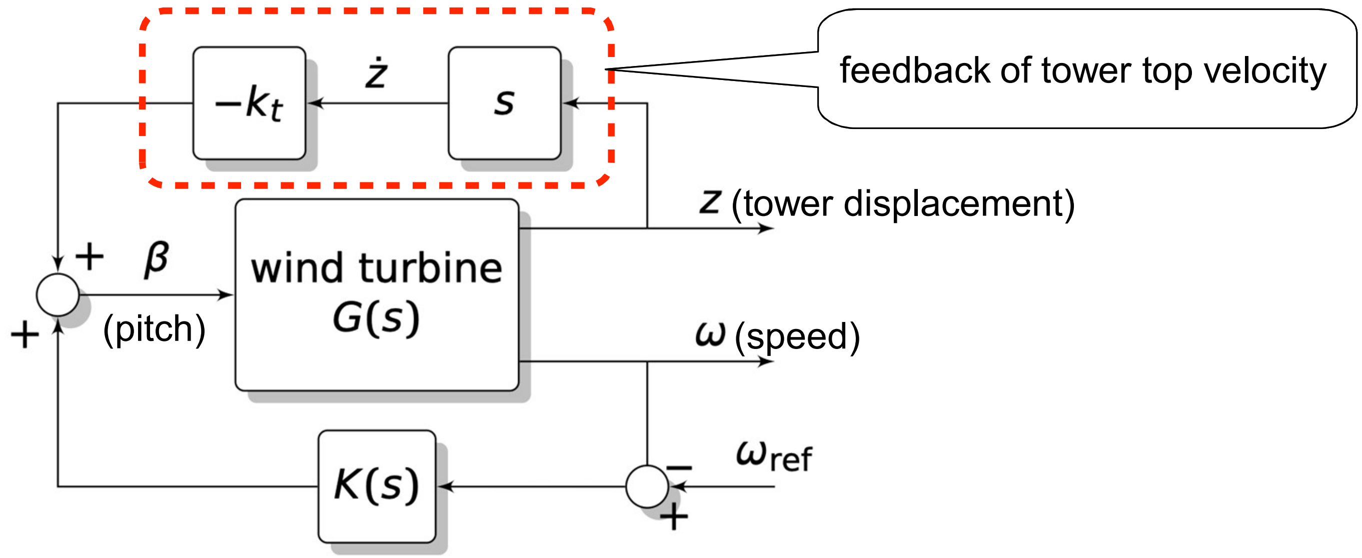
2. Parallel compensation

3. Add control DOF

4. Pitch-to-stall operation

2. Parallel compensation [2,3,4]

[2] W. E. Leithead and S. Dominguez, [3] T. J. Larsen and T. D. Hanson, [4] M. A. Lackner and M. A. Rotea

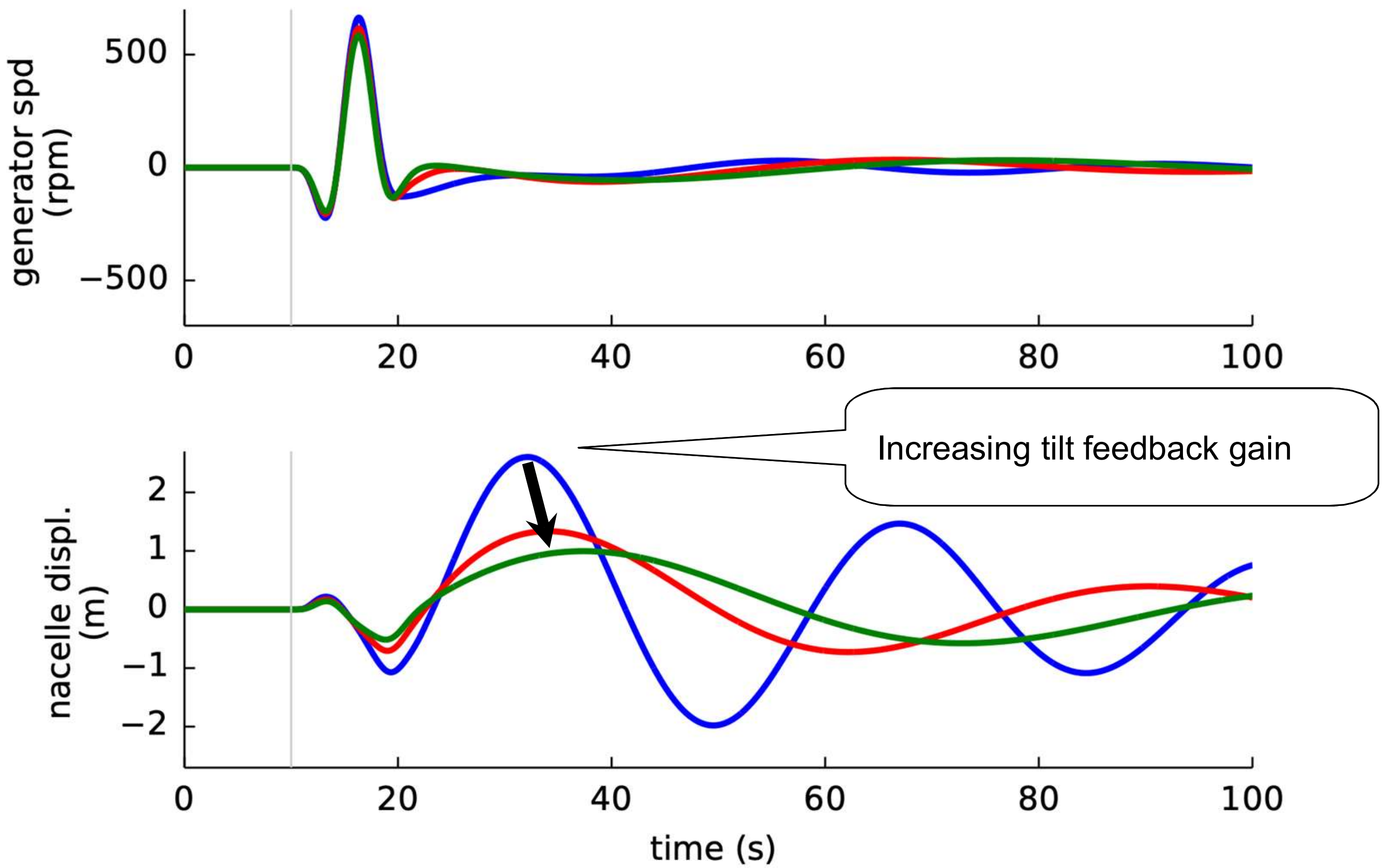


- Increases damping of tilt motion → place tilt mode poles deeper into LHP

- Still: fundamental limitations due to (almost) RHP zeros

2. Parallel compensation

⑩ Improves tilt damping, but generator speed response stays poor



Potential solutions

1. Reduce controller bandwidth

2. Parallel compensation

3. Add control DOF

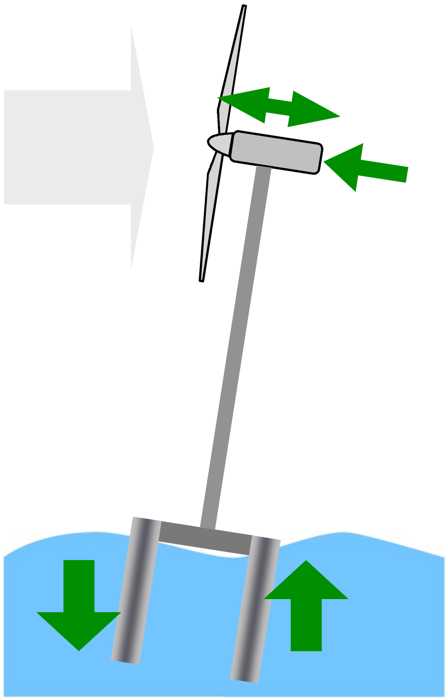
4. Pitch-to-stall operation

3. Add control degree of freedom [4,5]

[4] M. A. Lackner and M. A. Rotea, [5] B. Fischer

- Only genuine solution → no transmission zeros in MIMO model; no fundamental bandwidth limit

- Most obvious solution: use generator torque
  - Torque control directly affects power output
  - May end up in side-side oscillations (strong coupling)
  - Increases drive train loads
  - Not available on grid loss failure



- Alternative solutions:
  - Active mass damper in nacelle (feasible?)
  - Fast active ballast system

Potential solutions

1. Reduce controller bandwidth

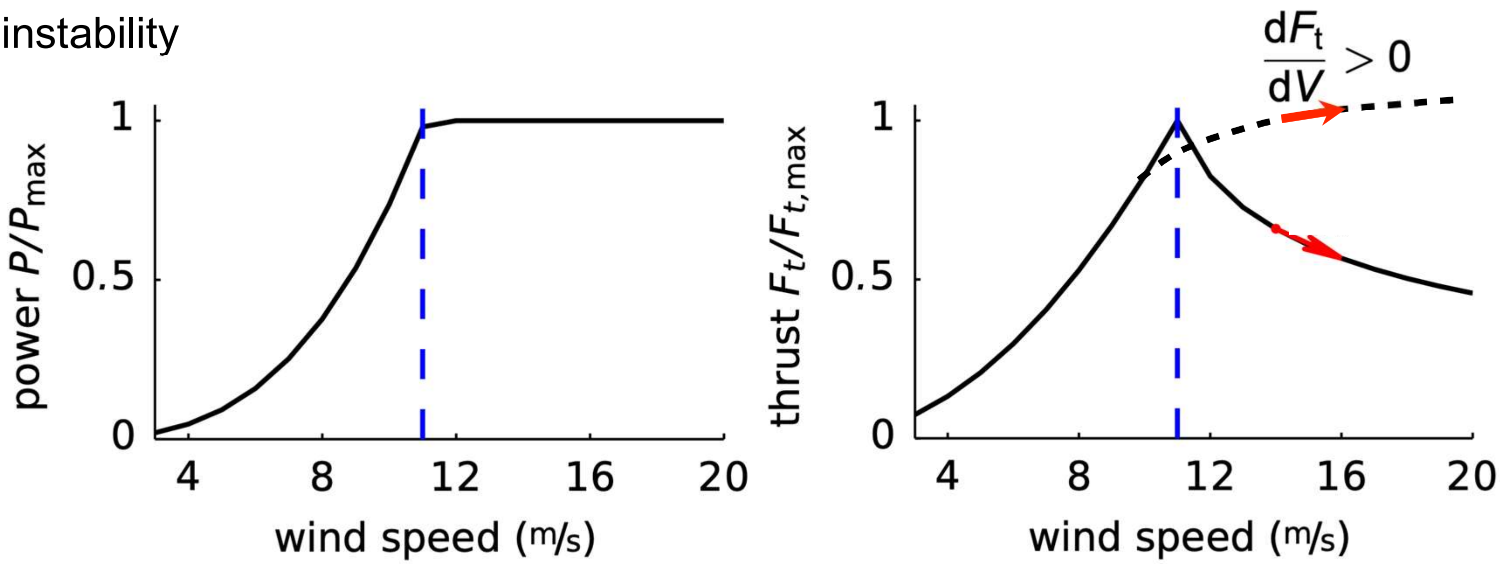
2. Parallel compensation

3. Add control DOF

4. Pitch-to-stall operation

4. Pitch-to-stall operation

- ➉ No static instability



- ➉ Difficult to model
- ➉ Potentially high loads due to blade stall
- ➉ Less opportunities to regulate power

Potential solutions - summary

1. Reduce controller bandwidth
   - Larger speed excursions
   - Generator over-speed shutdowns *or* lower speed and power set-point
2. Parallel compensation
   - Fundamental limitations due to RHP zeros
3. Add control DOF
   - No transmission zeros in MIMO model
   - Not a trivial solution
4. Pitch-to-stall operation
   - Modelling and loads

Future turbines

⑩ Future turbines will increase in size:

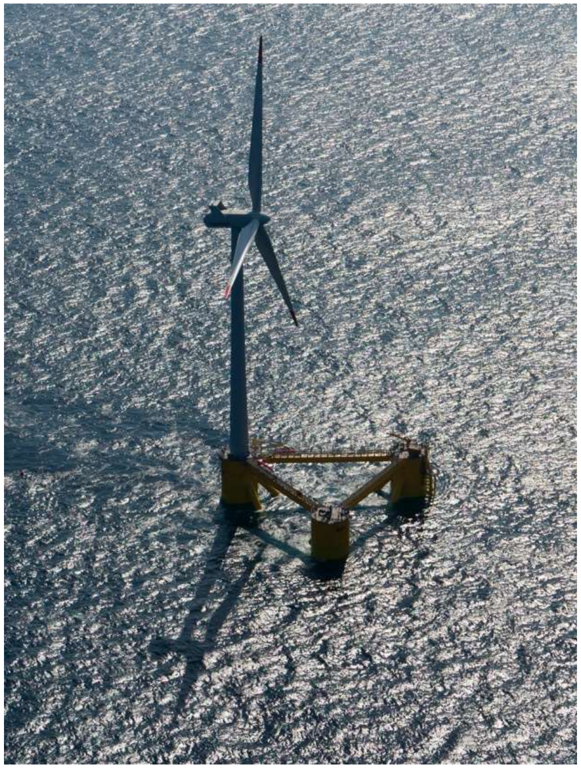
1. Analysis of larger rotors shows $\frac{dF_T}{dV}$ will increase in magnitude

2. Taller towers imply lower natural frequencies

$$z \approx -\frac{1}{2}\left(4\pi\zeta_{twr}f_{twr} + a_1\frac{dF_T}{dV}\right) \pm j2\pi f_{twr}$$

Summary

- The low-frequency lightly damped tilt mode of a floating wind turbine presents control challenges
  - Fundamental limits
- Modification of existing control strategies is absolutely necessary for pitch-to-feather operation
- No clear “best” solution
- Naturally motivates treating as multivariable control problem



WindFloat (Principle Power USA)

2012 American Control Conference
Fairmont Queen Elizabeth, Montréal, Canada
June 27-June 29, 2012

Control of floating wind turbines

G.J. van der Veen, I.J. Couchman, and R.O. Bowyer.

[1] J. Jonkman, Influence of control on the pitch damping of a floating wind turbine, 46th AIAA Aerospace Science Meeting, Reno, US, 2008.
[2] W. E. Leithead and S. Dominguez, Coordinated Control Design for Wind Turbine Control Systems, EWEC Athens, Greece, 2006.
[3] T. J. Larsen and T. D. Hanson, A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine, The Science of Making Torque from Wind, Journal of Physics: Conference Series 75, 2007.
[4] M. A. Lackner and M. A. Rotea, Structural control of floating wind turbines, Mechatronics, 2010.
[5] B. Fischer, Reducing rotor speed variations of floating wind turbines by compensation of non-minimum phase zeros, EWEA, 2012.