Individual Pitch Control

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Lecture #9
Controller Design for Wind Turbines and Wind Farms

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Schedule

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03.09.	2	Baseline Generator Torque Controller
04.09.	3	Collective Pitch Controller
05.09.	4	Filter Design
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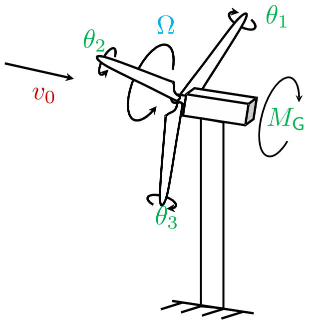
Individual Pitch Control and Other Concepts



Motivation

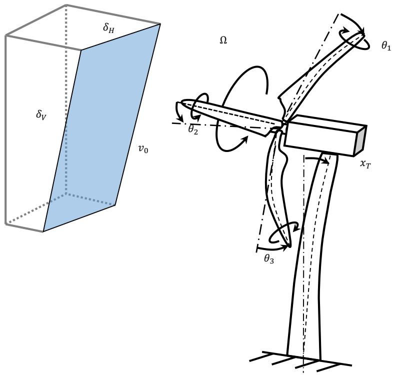
- a wind field is more complex than only rotor-effective wind speed v_0
- the size of modern wind turbines increase more and more
- modern wind turbines have more and more sensors available

Objectives

- Why could it be useful to control each blade individually and how to do it?
- What other control concepts are applied in wind energy?

Content

Individual Pitch Control



Main Idea

- modern wind turbines (WT) have three independent pitch actuators
- reducing asymmetrical aerodynamic loads from rotor-effective shears δ_H, δ_V, which are responsible for a significant contribution to fatigue loads
- adjustment of pitch θ_1, θ_2, and θ_3
- reduction of rotor yaw and pitch moment by introducing two control loops:
  - horizontal (H)
  - vertical (V)
- also reduction of 1P blade bending

Coleman Transformation

$$\underbrace{\begin{bmatrix} M_{\mathsf{V}} \\ M_{\mathsf{H}} \end{bmatrix}}_{\text{fixed}} = \underbrace{\frac{2}{3}\begin{bmatrix} \cos(\psi_1) & \cos(\psi_2) & \cos(\psi_3) \\ \sin(\psi_1) & \sin(\psi_2) & \sin(\psi_3) \end{bmatrix}}_{\mathsf{T_c}} \underbrace{\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}}_{\text{rotating}}$$

with $\psi_2 = \psi_1 + \frac{2\pi}{3}$ and $\psi_3 = \psi_1 + \frac{4\pi}{3}$

$$\underbrace{\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}}_{\text{rotating}} = \underbrace{\begin{bmatrix} \cos(\psi_1) & \sin(\psi_1) \\ \cos(\psi_2) & \sin(\psi_2) \\ \cos(\psi_3) & \sin(\psi_3) \end{bmatrix}}_{\mathsf{T_c}^{-1}} \underbrace{\begin{bmatrix} \theta_{\mathsf{V}} \\ \theta_{\mathsf{H}} \end{bmatrix}}_{\text{fixed}}$$

Coleman Transformation

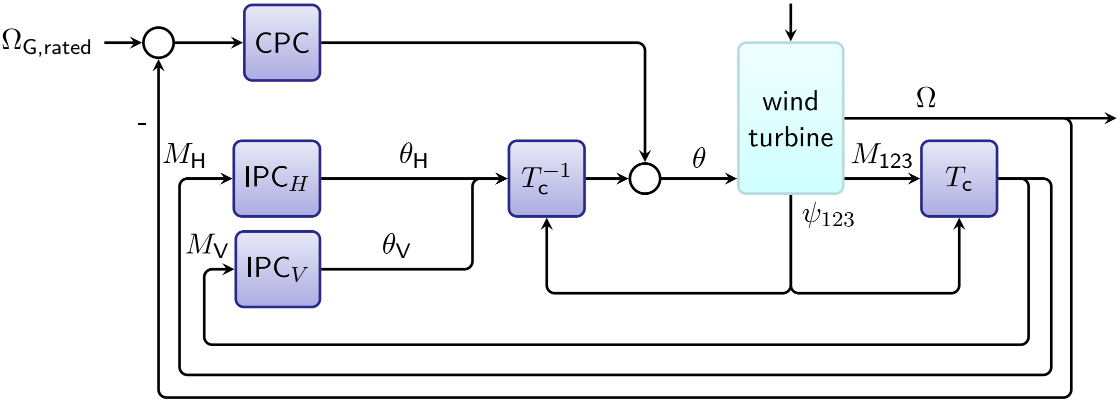
- transforms the load from the rotating axes to the non-rotating (fixed) axes
- from 3 blade root bending moments to 2 rotor moments
- rotor azimuth ψ as input
- based on Park's transformation [1] for three-phase electrical machines

Inverse Coleman Transformation

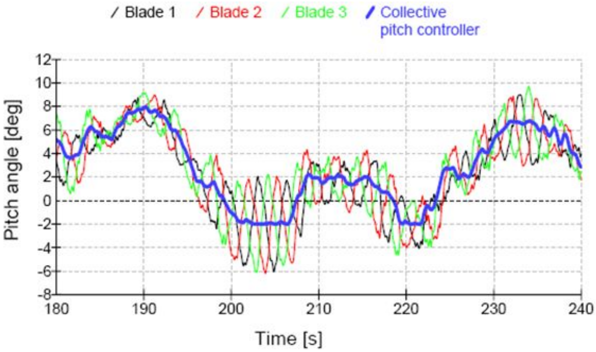
from horizontal and vertical pitch angle to 3 individual blade pitch angle

Implementation

- two independent and identical SISO controllers
- low bandwidth PI controllers with a notch filter at the blade passing frequency



Pitch Action

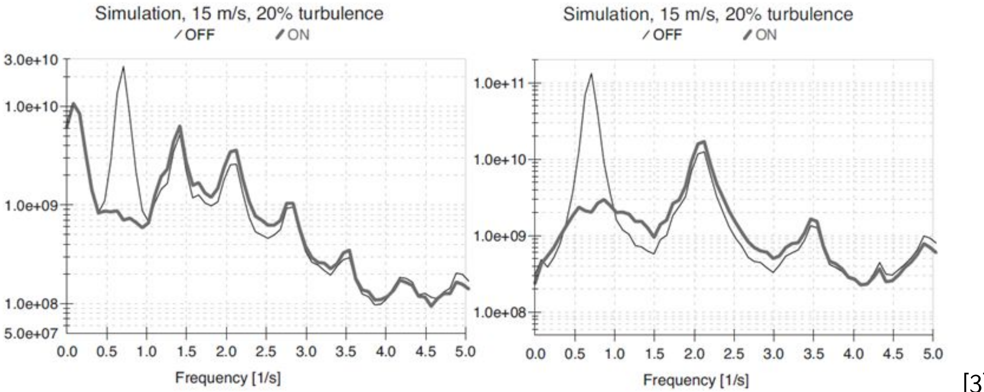


[2].

Resulting blade pitch signals

- three near-sinusoidal individual pitch demands around the collective pitch signal
- frequency: 1P
- phase-shifted by $2\pi/3$
- significantly increased pitch activity

Effect in Rotating Frame



[3]

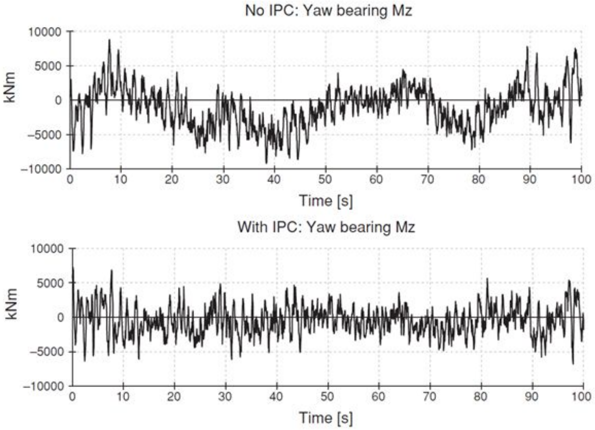
Reduction of 1P in ...

- blade root out of plane moment (left)
- rotating shaft bending moment (right)

Fatigue load reduction

- $\sim$ 20 % for blade root out of plane moment
- 30-40 % for rotating shaft bending moment

Effect in Fixed Frame



[3]

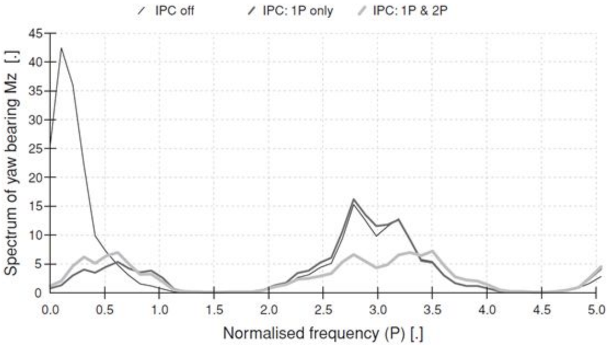
Time series of yaw bearing moment:

- IPC reduces the low frequency variation of the nacelle yawing moment
- this results in peak load reduction
- can be used to assist yaw control
- nacelle pitching moment is reduced in a very similar way

Second-harmonic IPC

Second-harmonic IPC

- dominant source of fatigue loading for a three-bladed WT on the non-rotating components is at 3P
- these loads can be reduced with 2P IPC
- achieved in exactly the same way as 1P IPC but sine and cosine arguments in Coleman Transformation multiplied by 2
- results in 2P pitch action

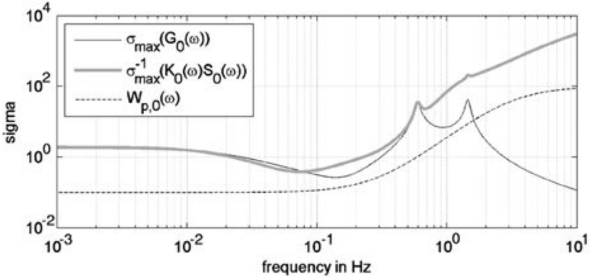


[3]

Design

Alternative Controllers

- the two H/V loops are not completely decoupled
- but they are nearly linear
- typical application for robust multivariable controllers like:
  - LQG [2]
  - H_∞ [4]
  - ℓ_1-Optimal [5]



Plot of pitch angle weighting function $W_{p,0}$; comparison with inverted maximum singular value of control sensitivity function K_0S_0 and maximum singular value of nominal plant G_0 for designing an H_∞ controller [from 4]

[4]

Sensors

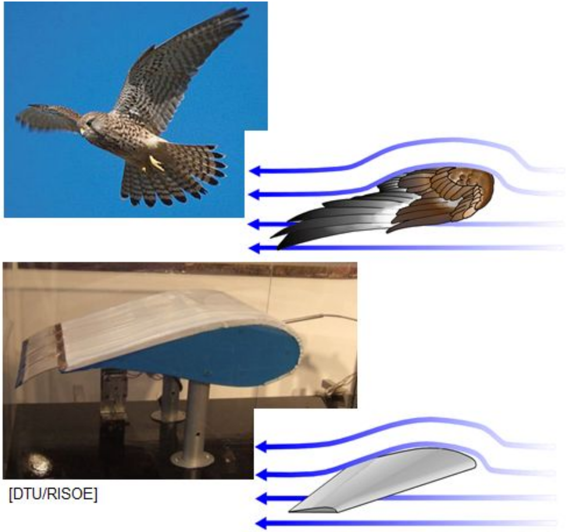
Further remarks:

- IPC requires a reliable sensor system
  - strain gauges are not reliable over 20 years
  - strain sensors based on fibre Bragg gratings are promising
- alternative sensor positions in the nacelle are imaginable
- IPC is phased out below rated
- IPC could also be used to generate a yaw moment and support the yaw actuator

[fos4X]

Temperature compensated fiber optic strain sensor „fos4Strain expert" from fos4X

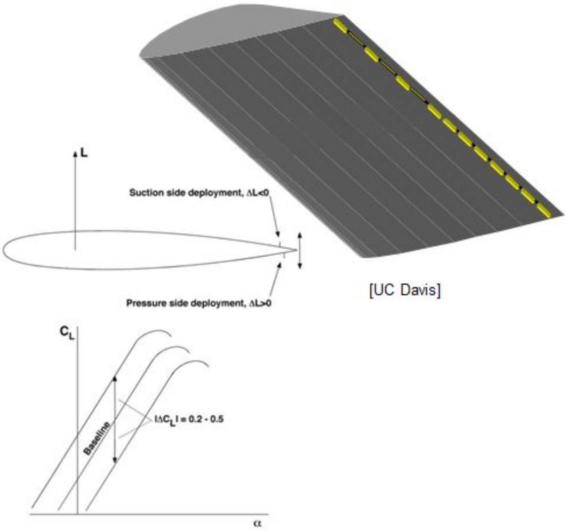
Smart Rotors I



Deformable Trailing Geometries:

- flaps are added to the trailing edge of the rotor blade (c.f. air planes)
- advantages: reduces extreme loads, less pitch activity, better exploitation of gusts
- disadvantages: high maintenance and service demands
- complex distributed control algorithms needed

Smart Rotors II

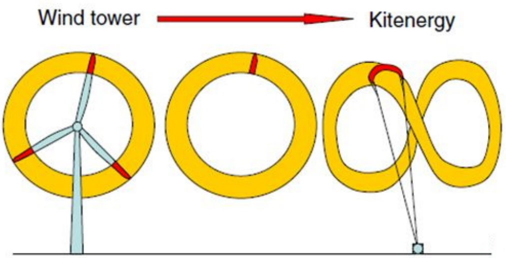


[UC Davis]

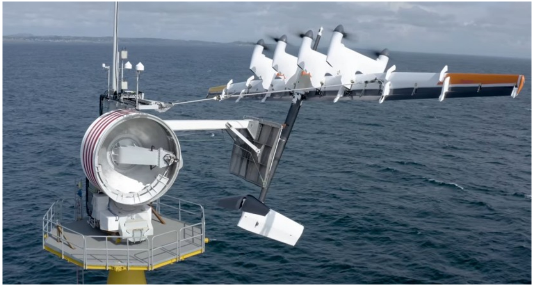
Microtabs:

- extendable Gurney-flaps are added to the trailing edge of the rotor blade (only on/off)
- advantages: reduces loads, low own consumption
- disadvantages: maintenance and service demands
- complex distributed control algorithms needed

Airborne Wind



[6],[youtube-AirborneWindEnergy]



[Makani]

- wind speed increases with height, but classical tower based WTs are limited in their height
- a flying wind energy converter gets rid of the massive structures of a classical WT
- benefits: much lighter, cheaper and more flexible systems
- types: energy generation on ground (kites) or on wings
- challenges: control, air traffic safety

Conclusion

- Why could it be useful to control each blade individually?

Asymmetric loads can be reduced!

- two independent and identical SISO controller loops
- based on direct measurement of the blade root bending moments
- Coleman Transformation to go from rotating frame to fixed frame and vice versa
- typical application for robust multivariable controllers (H_∞, LQG controllers, ...)

- What other control concepts are applied in wind energy?

A lot of innovative concepts are developed and tested in research!

- Smart Rotors with additional actuator to influence the blade aerodynamics
- Flying Wind Energy Converters to overcome the limited structural height of WTs

Quick check on learning objectives

After this lectures you should be able to...

- describe the control loop of individual pitch control.
- describe the Coleman transformation.
- describe the effect of individual pitch control.
- describe how we can measure blade loads.
- describe how smart rotor and kites work and why they are promising technologies.

References

[1] R. H. Park. "Two-reaction theory of synchronous machines generalized method of analysis-part I". In: *Transactions of the American Institute of Electrical Engineers* 48 (3 1929), pp. 716–727. DOI: 10.1109/T-AIEE.1929.5055275.

[2] E. A. Bossanyi. "Individual Blade Pitch Control for Load Reduction". In: *Wind Energy* 6 (2 2003), pp. 119–128. DOI: 10.1002/we.76.

[3] T. Burton, N. Jenkins, D. Sharpe, and E. Bossanyi. *Wind Energy Handbook*. New York, USA: John Wiley & Sons, 2011.

[4] M. Geyler and P. Caselitz. "Robust Multivariable Pitch Control Design for Load Reduction on Large Wind Turbines". In: *ASME Journal of Solar Energy Engineering* 130 (2008). DOI: 10.1115/1.2931510.

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[6] L. Fagiano, M. Milanese, and D. Piga. "Optimization of airborne wind energy generators". In: *International Journal of Robust and Nonlinear Control* 22 (18 2012), pp. 2055–2083. DOI: 10.1002/rnc.1808.

Please let me know if you have further questions!

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