Filter Design

Prof. Dr.-Ing. David Schlipf

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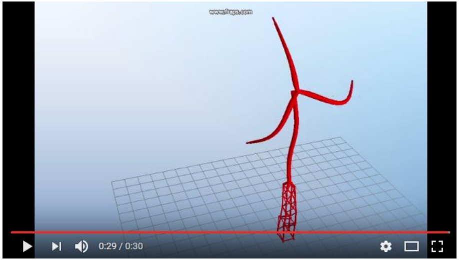
Lecture #4
Controller Design for Wind Turbines and Wind Farms

Hochschule Flensburg
University of Applied Sciences

SWE Stuttgart Wind Energy
@ Institute of Aircraft Design

Wind Energy Technology Institute

Filter Design, Tower and Drive Train Damper



Motivation:
Wind Turbines are very flexible structures...

- Modes from tower, blades, shaft...
- Coupling with each other and rotation.
- Not considered in baseline controller design.

→ Might result in unwanted resonance!

Objectives

- How can we avoid resonance with important modes by filtering?
- How can we damp tower and drive train torsional vibrations?

Schedule

02.09.	1	Controller Design Objectives and Modeling
03.09.	2	Baseline Generator Torque Controller
04.09.	3	Collective Pitch Controller
05.09.	4	Filter Design
06.09.	5	Tower Damper
09.09.	6	Advanced Torque Controller
10.09.	7	Wind Field Generation
11.09.	8	Steady State Calculations
12.09.	9	Individual Pitch Control
13.09.	10	Lidar-Assisted Control I
16.09.	11	Lidar-Assisted Control II
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18.09.	13	Wind Farm Control
19.09.	14	Floating Wind Control I
20.09.	15	Floating Wind Control II

Contents

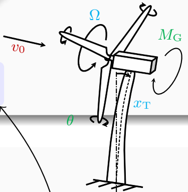
Reduced model for controller design

Structural dynamics

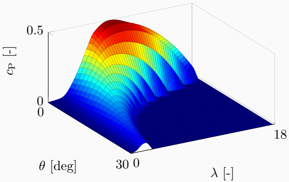
Fuerza de empuje

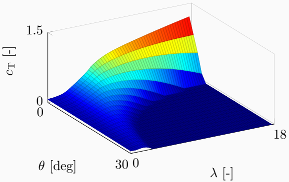
rotor motion: $J\dot{\Omega} = \boxed{M_\mathsf{a}} - M_\mathsf{G} r_\mathsf{GB}$

tower motion: $m\ddot{x}_\mathsf{T} + c\dot{x}_\mathsf{T} + k(x_\mathsf{T} - x_\mathsf{T0}) = \boxed{F_\mathsf{a}}$



Aerodynamics





torque: $\boxed{M_\mathsf{a} = \frac{1}{2}\rho\pi R^2 \frac{c_\mathsf{P}(\lambda,\theta)}{\Omega} v_\mathsf{rel}^3}$ thrust: $\boxed{F_\mathsf{a} = \frac{1}{2}\rho\pi R^2 c_\mathsf{T}(\lambda,\theta) v_\mathsf{rel}^2}$

tower top velocity

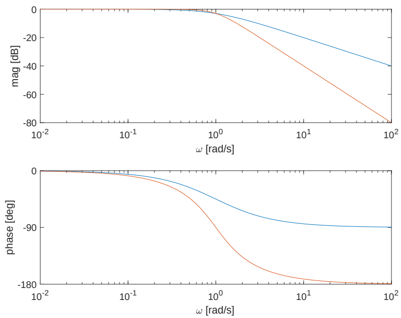
with tip speed ratio $\lambda = \frac{\Omega R}{v_\mathsf{rel}}$ and relative wind speed $v_\mathsf{rel} = v_0 - \dot{x}_\mathsf{T}$

Low pass filter design

el filtro de primer orden decae con pendiente
10 db por salto de frecuencia

en f=1 rad/s en 3db la amplitud cae al 70% y se retrasa 45º es aprox 0.8 seg
en f=10 rad/s en 20db la amplitud cae al 10% y se retrasa 85º casi un cuarto
en f=100 rad/s en 40db la amplitud cae al 1% y se retrasa 90º un cuarto de periodo

Ojo con el delay de tiempo



With $\omega_{\text{cut-off}} = 1\,\text{rad/s}$:

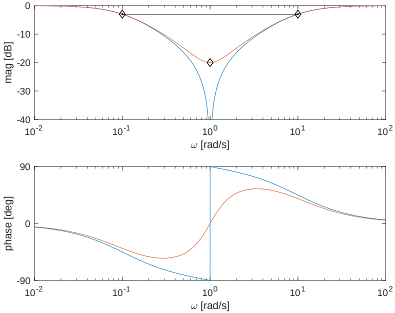
1st order: $$\frac{\omega_{\text{cut-off}}}{s + \omega_{\text{cut-off}}}$$

2nd order Butterworth: $$\frac{\omega_{\text{cut-off}}^2}{s^2 + \sqrt{2}\omega_{\text{cut-off}} s + \omega_{\text{cut-off}}^2}$$

- Used to filter out noise above highest eigenfrequency.
- Usually first or second order Butterworth filter is used.
- Main problem: phase and thus time delay!

→ Use with care! Better place it at a higher frequency and use a notch filter.

Notch filter design



With $\omega_1 = 0.1\,\text{rad/s}$ and $\omega_2 = 10\,\text{rad/s}$ or $\omega_{\text{notch}} = \sqrt{\omega_2\omega_1} = 1\,\text{rad/s}$, bandwidth $b = \omega_2 - \omega_1$, and depth d, $\omega_{1/2} = \frac{\sqrt{b^2 + 4\omega_{\text{notch}}^2} \pm b}{2}$:

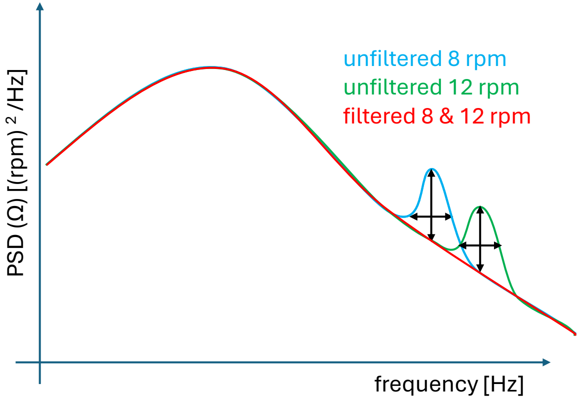
$$\text{Butterworth: } \frac{s^2 + \omega_2\omega_1}{s^2 + (\omega_2 - \omega_1)s + \omega_2\omega_1}$$

$$\text{adjusted notch filter: } \frac{s^2 + bds + \omega_{\text{notch}}^2}{s^2 + b\ s + \omega_{\text{notch}}^2}$$

- Used to filter out certain frequencies to avoid resonances.
- Usually adjusted notch filter used due to better numerical and dynamic properties.

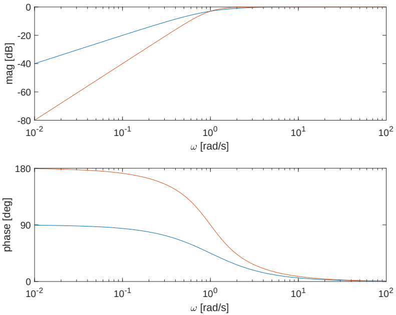
Dynamic notch filter design

se filtran señales en el entorno de 3p pero estas cambia según la velocidad de rotación



- 3P frequency changes with mean rotor speed.
- 3P in generator speed causes unnecessary pitch and torque controller action.
- Low pass is used to get mean rotor speed (usually 4-5 times slower than closed-loop frequency).
- Adjusted notch filter with relative bandwidth (usually 30 to 40% of notch frequency) used to obtain "natural" spectra.

High pass filter design



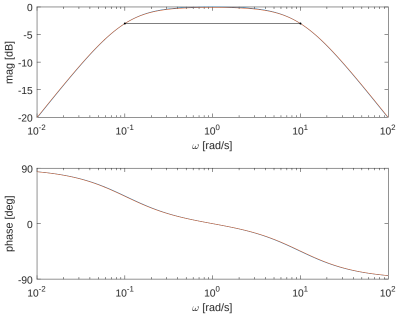
With $\omega_{\text{cut-in}} = 1\,\text{rad/s}$:

$$\text{1st order: } \frac{s}{s + \omega_{\text{cut-in}}}$$

$$\text{2nd order Butterworth: } \frac{s^2}{s^2 + \sqrt{2}\omega_{\text{cut-in}} s + \omega_{\text{cut-in}}^2}$$

- Used to filter out steady state.
- Usually first or second order Butterworth filter is used.

Band pass filter design



With $\omega_1 = 0.1\,\text{rad/s}$ and $\omega_2{=}10\,\text{rad/s}$ or $\omega_{\text{band}} = \sqrt{\omega_2\omega_1} = 1\,\text{rad/s}$, bandwidth $b = \omega_2 - \omega_1$:

$$\text{high+low pass: } \frac{\omega_2 s}{s^2 + (\omega_2 + \omega_1)s + \omega_2\omega_1}$$

$$\text{Butterworth: } \frac{bs}{s^2 + bs + \omega_{\text{band}}^2}$$

es utilizado para el filtrado de la frecuencia de resonancia del generador

- Used to let pass certain frequencies.
- Usually 2nd order Butterworth filter used.

Conclusion

Main questions

- How can we avoid resonance with important modes by filtering?
- How can we damp tower and drive train torsional vibrations? Next lecture

With low pass and notch filters

- A low pass is usually used for filtering out noise: Trade-off filter effect vs. time delay.
- A notch filter is used for specific frequencies.

Quick check on learning objectives

After this lectures you should be able to...

- ...model the basic dynamics of the rotor and tower of a wind turbine.
- ...know when to use a low pass or a notch filter.
- ...design a low pass filter.
- ...design a notch filter.
- ...design a high pass filter.
- ...design a band pass filter.

Please let me know if you have further questions!

Prof. Dr.-Ing. David Schlipf
David.Schlipf@HS-Flensburg.de
www.hs-flensburg.de/go/WETI

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