Control of variable speed wind turbines

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Objective:

- Understand control technology
- Understand a typical wind turbine controller
- How to design a basic wind turbine controller

Largest Wind Turbines

https://www.ge.com/renewableenergy/wind-energy/turbines/haliade-x-offshore-turbine

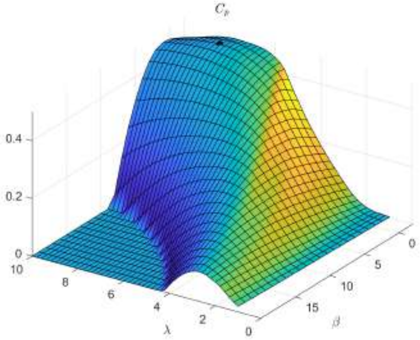
Control for power production

Fundamental relations:

- $\mathrm{Power} = \mathrm{Q_d}\omega_\mathrm{g}$
  Q_d= Generator Torque
  ω_g = Generator Speed

- $\mathrm{Power} = \frac{1}{2}\rho\pi\mathrm{R}^2\mathrm{C_p}(\lambda, \beta)\mathrm{V}^3$
  ρ = air density
  R = rotor radius
  V = effective windspeed
  C_p= power coefficient
  β= pitch angle

- tip speed ratio $\lambda = \frac{R\omega_g/G}{V}$
  G = Gear box ratio



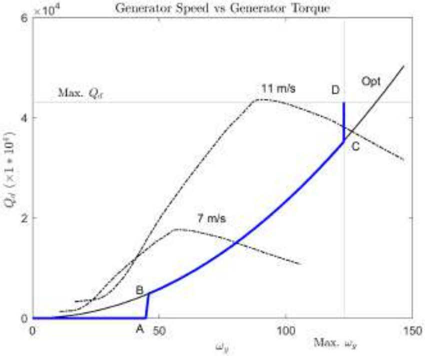
VS-VP (Below rated)

Fundamental relation:

- $Q_d = \frac{\pi \rho R^5 C_p(\lambda,\beta)}{2\lambda^3 G^3}\omega_g^2$
- $Q_d^{opt} = \frac{\pi \rho R^5 C_p^{opt}}{2\lambda_{opt}^3 G^3}\omega_g^2$

Typically we have:

- Efficiency
  94.4%
- Limit on gen. speed
  Max=123 rad/s
- Limit on generator power
  Max Power= 5 MW
  Max Q_d=43 kNm



VS-VP (Below rated)

Fundamental relation:

- $P = \frac{\pi \rho R^5 C_p(\lambda,\beta)}{2\lambda^3 G^3} \omega_g^3$
- $P^{opt} = \frac{\pi \rho R^5 C_p^{opt}}{2\lambda_{opt}^3 G^3} \omega_g^3$

Typically we have:

- Efficiency
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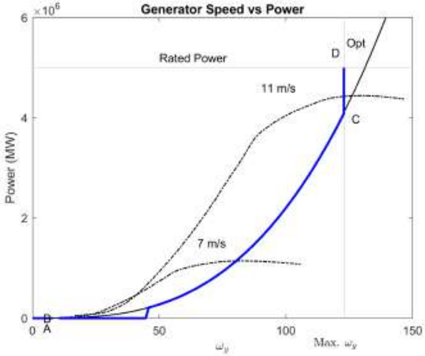
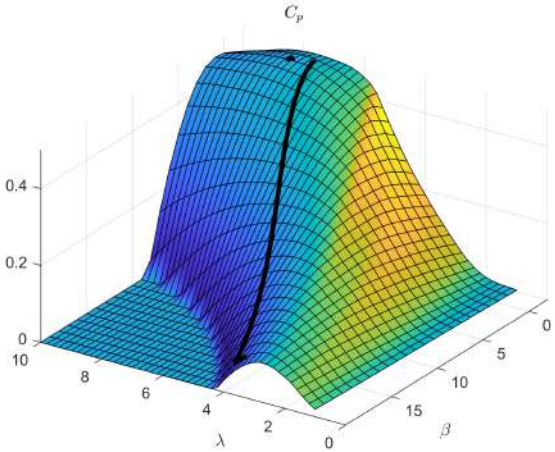
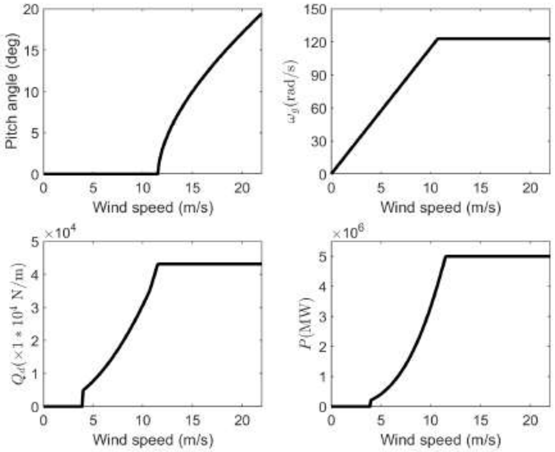


VS-VP (Above rated): Reduce C_p



Shading is the gradient of C_p

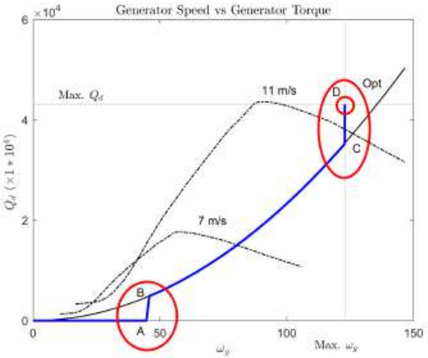
VS-VP (Above rated): Reduce C_p



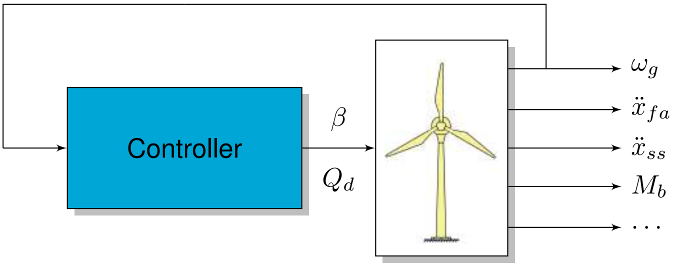
The feedback control loops

3 feedback loops:

1. Start up $\rightarrow$ PI
2. Torque control $\rightarrow$ PI
3. Pitch control
   $\rightarrow$ gain-scheduled PI(D)



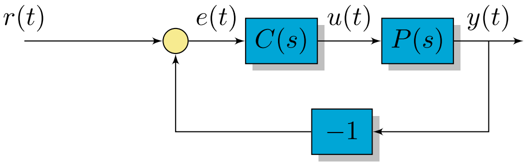
The controller



The controller

Condition	No control	Feedback loop 1	Optimal power tracking	Feedback loop 2	Feedback loop 3
$\omega_g < \omega_{A^*}$	✓				
$\omega_g < \omega_B$	-	✓			
$Q_d > k_{opt}\omega_B^2$	-	-	✓		
$Q_d > k_{opt}\omega_{max}^2$	-	-	-	✓	
$Q_d > Q_d^{max}$	-	-	-	-	✓

Feedback loop



Important relation

$$y = \underbrace{\frac{P(s) \times C(s)}{I + P(s) \times C(s)}}_{T(s)} r + \underbrace{\frac{I}{I + P(s) \times C(s)}}_{S(s)} v$$

or

$$y = \frac{L(s)}{I + L(s)} r + \frac{I}{I + L(s)} v$$

with $L(s) = P(s) \times C(s)$

What do you need?

Control objective (Power production, load reduction)

Require: Simple linear models. To:

- indicate stability issues (gain margin, phase margin)
- look at the responsiveness of the controller (cross over frequency)
- look at damping (look at the poles of the closed-loop system)
- look at the systems response(steps in wind)

Also require: High fidelity models (nonlinear). To:

- do advanced load calculations (FAST, Bladed, HAWC, etc)

Linear differential equations

What are $C(s)$ and $P(s)$? Linear differential equations

Example: $\dot{y} = K_{sys}u$ Think of u=force and y=velocity

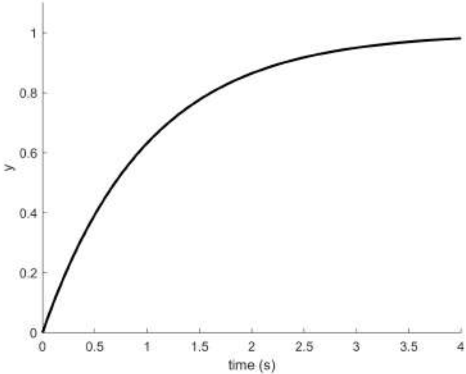
$\mathcal{L}(\dot{y}) = sy$ and $\mathcal{L}(\ddot{y}) = s^2y$ Where $\mathcal{L}(.)$ is the $\mathcal{L}$aplace operator

So, $P(s) = \frac{K_{sys}}{s}$

Loops 1, 2, 3

are of the form, $P(s) = \frac{-K_{sys}(V)}{s} + H(V,s)$
where $H(V,s)$ is structural dynamics (high frequent??)

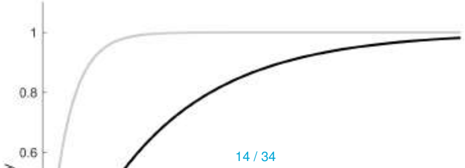
Example integrator



Plant:
P=$\frac{K_{sys}}{s}$

Proportional control:
C=K

Open loop:
PC=$\frac{KK_{sys}}{s}$



Dynamic response

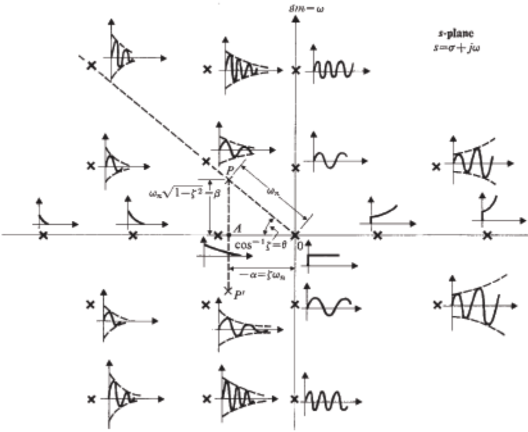
Characterized by:
Poles of CL(s)or
Zeros of I+L(s)

Impulse response:
$y = e^{st}$

Ex: First order:
$\frac{1}{\tau s+1}$
1 pole at s=$-\frac{1}{\tau}$

Ex: Second order:
$\frac{1}{s^2+2\omega_n\zeta+\omega_n^2}$
2 poles at
s=$-\omega_n\zeta \pm \omega_n\sqrt{1-\zeta^2}i$

Issue with FB: Stability!!!



Stability (simple)

Remember:

$$y = \frac{L(s)}{I + L(s)} r + \frac{I}{I + L(s)} v$$

It is sufficient to consider the imaginary axis ($s = i\omega$):

$$y = \frac{L(i\omega)}{I + L(i\omega)} r + \frac{I}{I + L(i\omega)} v$$

It is instinctive to state that the system is unstable if:

$$L(i\omega) = -I$$

Stability, PM and GM

So we want:

$$L(i\omega) \neq -I \qquad \forall\omega$$

A system is unstable if:

$$|L(i\omega)| = I \qquad \text{and} \qquad \angle L(i\omega) = -180$$

for one of the ω's

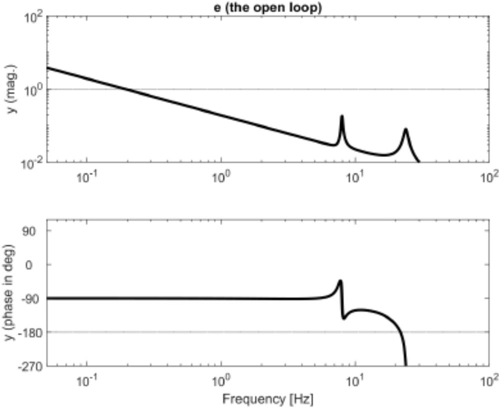
Goal stay far away from this point!!

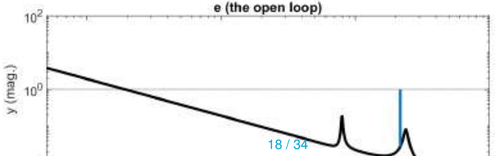
Tool: Gain and Phase margin

GM: the gain where $\angle L(i\omega) = -180$ (typical $>$ 3)
PM: the phase where $|L(i\omega)| = I$ (typical $>$ 40 degrees)

First we need Bode.

Bode





Bode plot:

- Bode: plot$(\omega, |L(i\omega)|)$ and

Loop Shaping

Key Idea: Shape $L(s)$ using Nyquist/Bode for closed-loop performance and stability

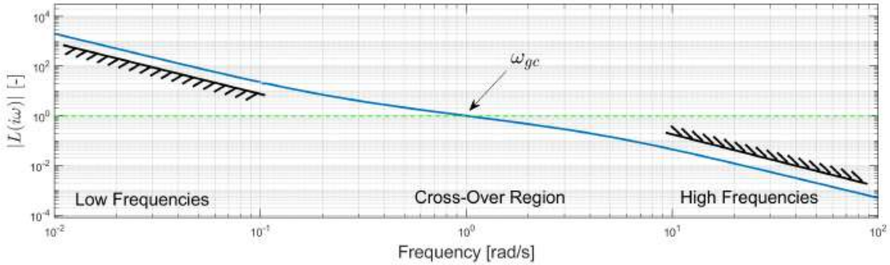
How (I): $C(s) = \frac{L_d(s)}{P(s)}$ where L_d is desired loop transfer function

How (II): place poles and zeros using Bode/Nyquist to get desired loop transfer function

Three key areas:

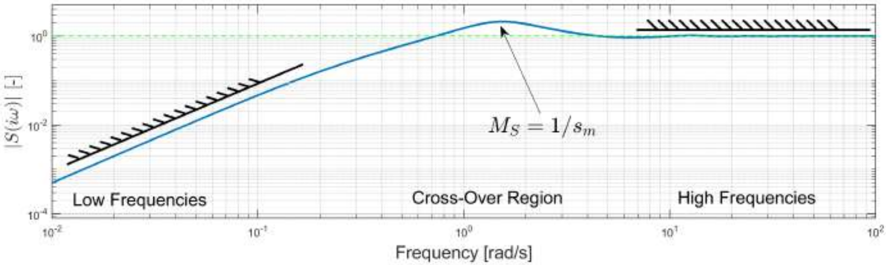
1. Low Frequencies, Load disturbance attenuation (High gain)
2. Cross-Over region, Robustness (Take care of margins)
3. High Frequencies, High frequency measurement noise (Low gain)

Loop Shaping: Loop Transfer Function



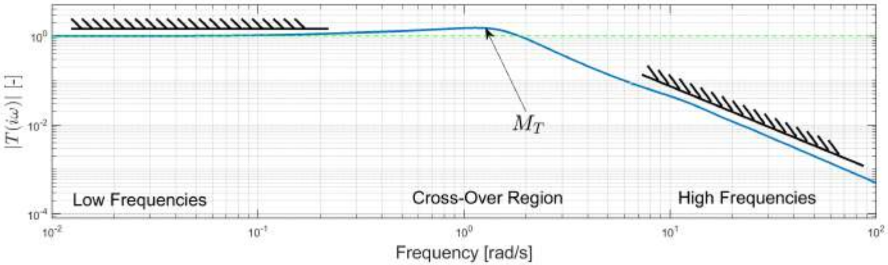
- Low Frequencies, High gain
- High Frequencies, Low gain
- Cross-Over region, Stability Margins, (PM=30^o, 45^o, 60^o equals Slope $-5/3$, $-3/2$, $-4/3$)

Loop Shaping: Sensitivity



- Low Frequencies, Low gain, Disturbance rejection
- High Frequencies, Gain=1, No difference between OL or CL
- Cross-Over region, Inevitable Peak M_S, OL will outperform CL at some freq.

Loop Shaping: Compl. Sensitivity



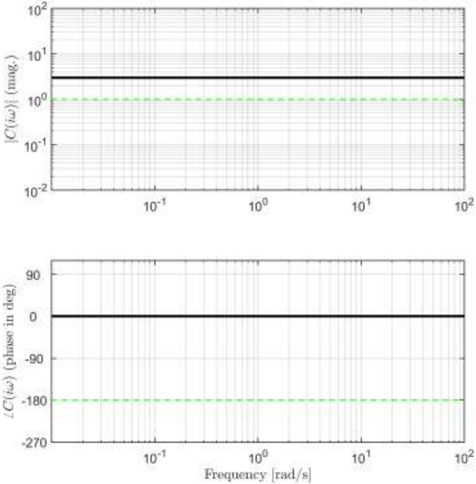
- Low Frequencies, Gain=1, Tracking of the reference
- High Frequencies, Low gain, No tracking of the reference
- Cross-Over region, Inevitable Peak M_T, Remember the equality $S + T = I$, Peak in S results in peak in T

Control elements

We have e.g.:

- P-action
- I-action
- D-action
- Low pass filter
- Notch
- PI
- PID
- Lead-lag

$C(s) = K_p$

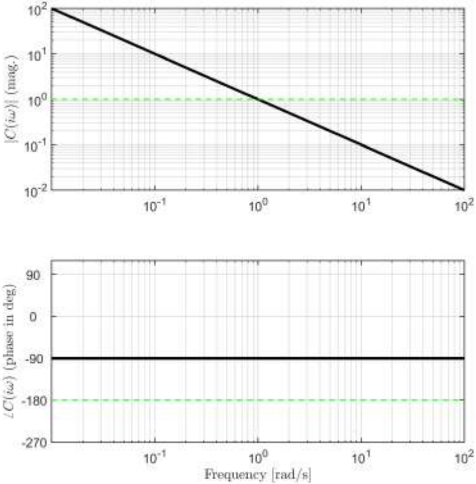


Control elements

We have e.g.:

- P-action
- I-action
- D-action
- Low pass filter
- Notch
- PI
- PID
- Lead-lag

$$C(s) = \frac{K_i}{s} \quad \text{or} \quad \left(\frac{T_i}{s}\right)$$

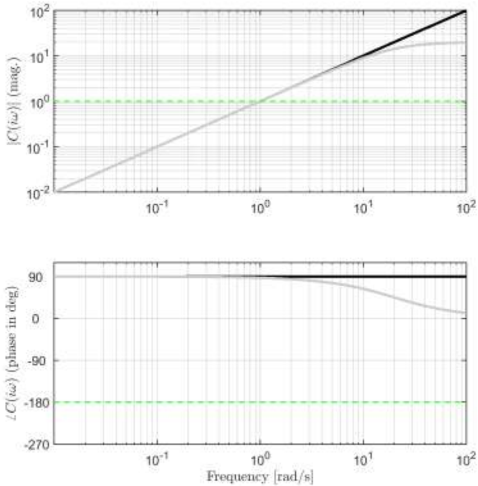


Control elements

We have e.g.:

- P-action
- I-action
- D-action
- Low pass filter
- Notch
- PI
- PID
- Lead-lag

$C(s) = K_d s$ or $\left(\frac{K_d s}{T_f s+1}\right)$

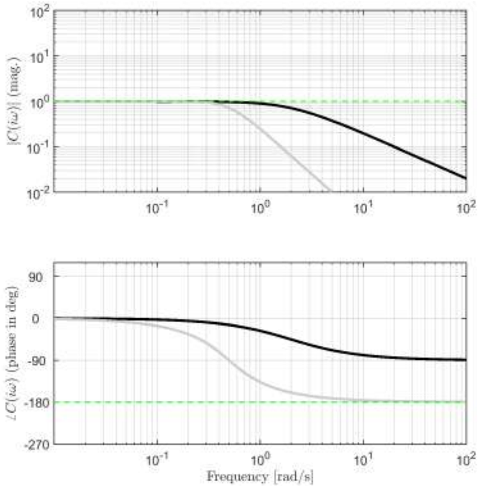


Control elements

We have e.g.:

- P-action
- I-action
- D-action
- Low pass filter
- Notch
- PI
- PID
- Lead-lag

$C(s) = \frac{1}{\tau s+1}$ or $\frac{\omega^2}{s^2+2\omega\beta s+\omega^2}$

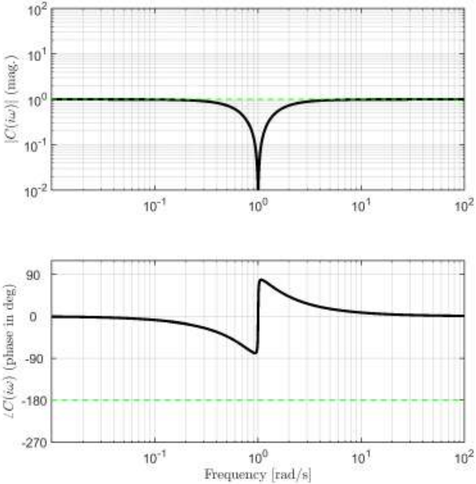


Control elements

We have e.g.:

- P-action
- I-action
- D-action
- Low pass filter
- Notch
- PI
- PID
- Lead-lag

$$C(s) = \frac{s^2+2\omega\beta_1 s+\omega^2}{s^2+2\omega\beta_2 s+\omega^2}$$

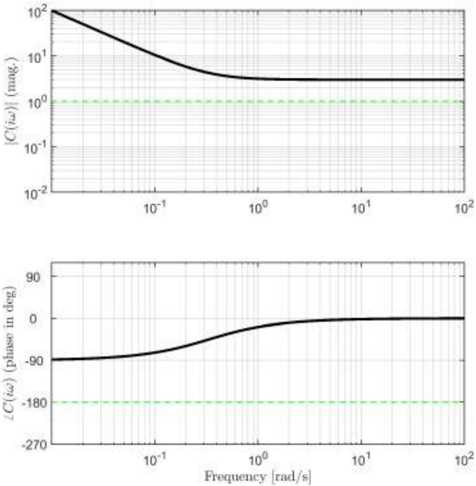


Control elements

We have e.g.:

- P-action
- I-action
- D-action
- Low pass filter
- Notch
- PI
- PID
- Lead-lag

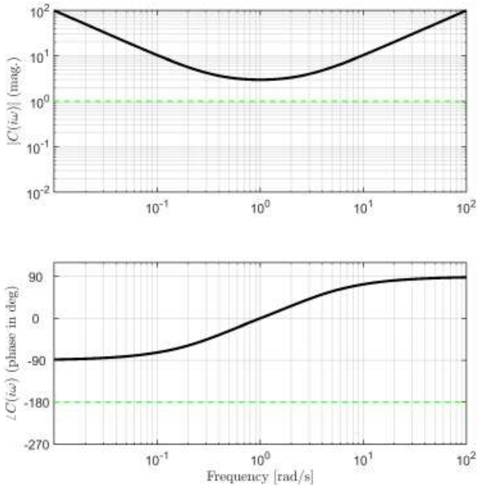
$$C(s) = \quad K_p \left(1 + \frac{T_I}{s}\right)$$



Control elements

We have e.g.:

- P-action
- I-action
- D-action
- Low pass filter
- Notch
- PI
- PID
- Lead-lag

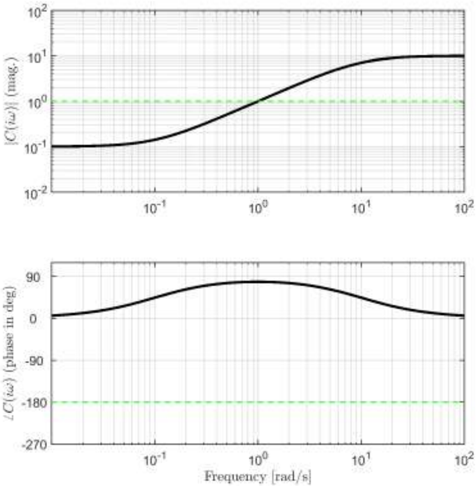


$$C(s) = \qquad K_p + \frac{K_i}{s} + K_d s$$

Control elements

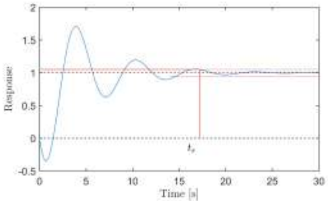
We have e.g.:

- P-action
- I-action
- D-action
- Low pass filter
- Notch
- PI
- PID
- Lead-lag

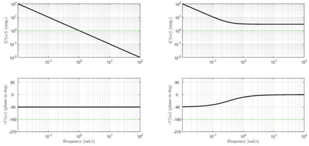


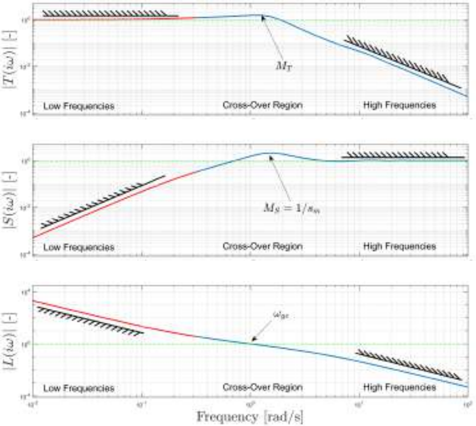
$$C(s) = \frac{\tau_1 s+1}{\tau_2 s+1}$$

Design process (Tracking): Low Frequencies



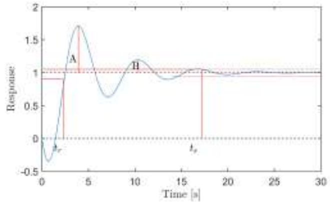
$e.g.$ I or PI



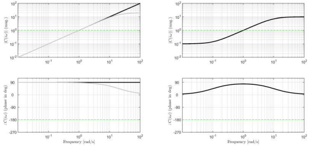


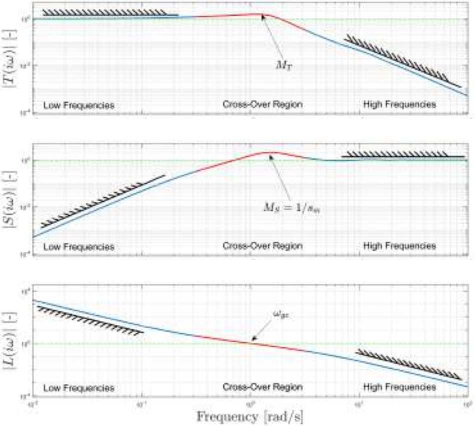
Reduce steady state errors by increasing the loop gain

Design process (Tracking): Cross-Over



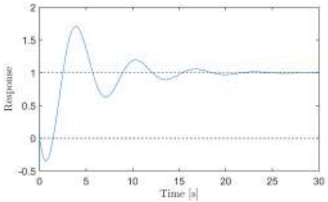
$e.g.$ D or Lead-Lag



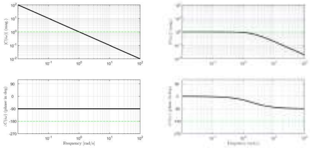


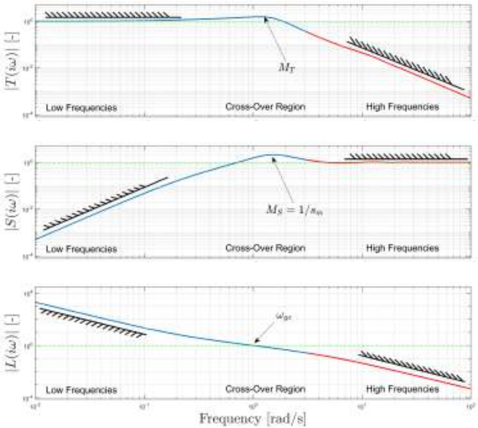
Increase the phase to satisfy stability margins

Design process (Tracking): High frequencies



e.g. I or Low-Pass



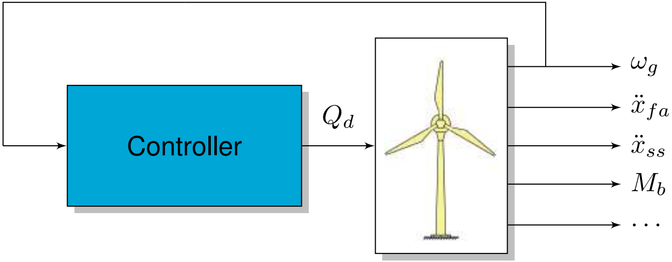


Reduce the gain to mitigate the effect of measurement noise

Design process (Tracking)

- Determine gain cross-over frequency ($|L(i\omega_{gc})|$ crosses 1)
- Add low pass filter to suppress the effect of high frequent dynamics (integrator, low-pass, notch)
- Add phase (D-action, lead-lag)
- Set cross-over frequency (P-action)
- Reference tracking (I-action)

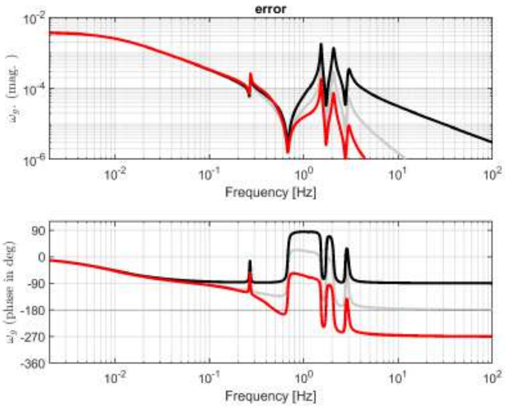
Torque control



Torque control: PI+

Reference tracking:

- $L(s)$
- Add LP $(1^{st}, 2^{nd})$



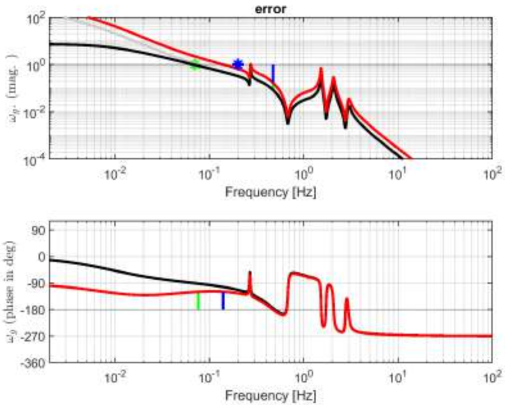
L(s):

- $P(s)LP(s)$

Torque control: PI+

Reference tracking:

- $L(s)$
- Add LP $(1^{st}, 2^{nd})$
- Tune Gain
- Add I-action
- Add more gain



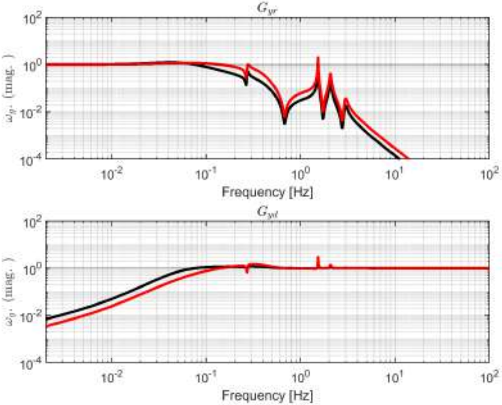
L(s):

$$-2e3\left(1+\frac{0.25}{s}\right)P(s)LP(s)$$
$$-5e3\left(1+\frac{0.25}{s}\right)P(s)LP(s)$$

Torque control: PI+

Reference tracking:

- $L(s)$
- Add LP $(1^{st}, 2^{nd})$
- Tune Gain
- Add I-action
- Add more gain
- $\frac{L(s)}{1+L(s)}$



L(s):

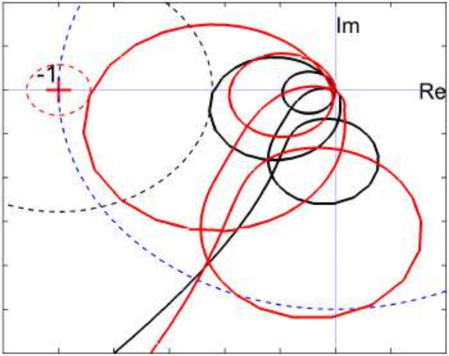
$-2e3\left(1+\frac{0.25}{s}\right)P(s)LP(s)$

$-5e3\left(1+\frac{0.25}{s}\right)P(s)LP(s)$

Torque control: PI+

Reference tracking:

- $L(s)$
- Add LP $(1^{st}, 2^{nd})$
- Tune Gain
- Add I-action
- Add more gain
- Nyquist



L(s):

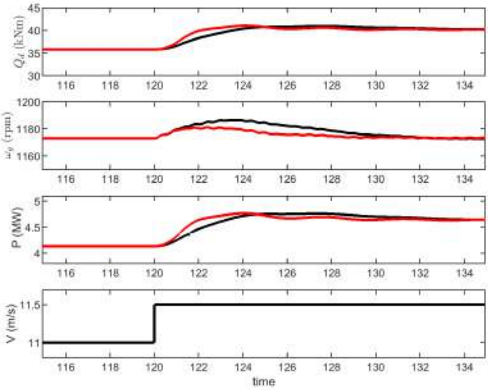
$$\text{-}2e3\left(1+\frac{0.25}{s}\right)P(s)LP(s)$$

$$\text{-}5e3\left(1+\frac{0.25}{s}\right)P(s)LP(s)$$

Torque control: PI+

Reference tracking:

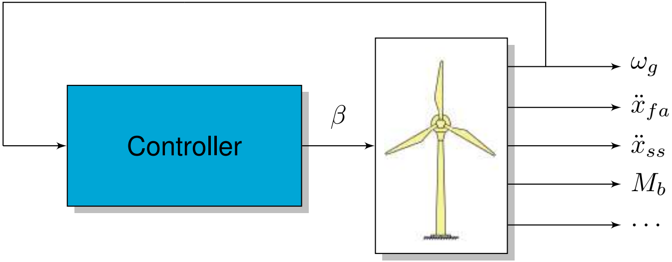
- $L(s)$
- Add LP $(1^{st}, 2^{nd})$
- Tune Gain
- Add I-action
- Add more gain
- Time Domain



L(s):

$$-2e3\left(1+\frac{0.25}{s}\right)P(s)LP(s)$$
$$-5e3\left(1+\frac{0.25}{s}\right)P(s)LP(s)$$

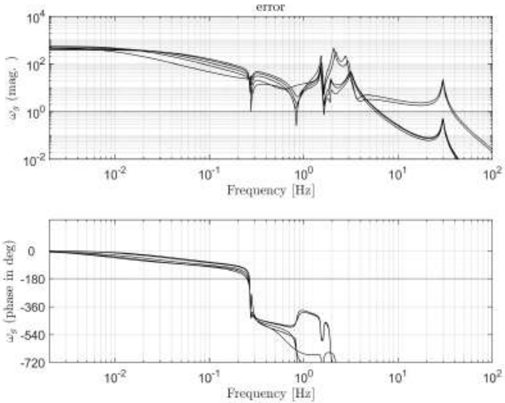
Pitch control



Pitch control: PI +

Reference tracking:

- $L(s)$



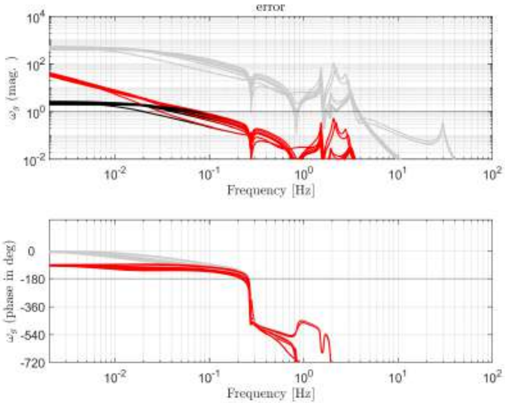
L(s):

- $P(s)$

Pitch control: PI +

Reference tracking:

- $L(s)$
- Add LP $({1^{st}}, {2^{nd}})$
- Tune Gain
- Add I-action



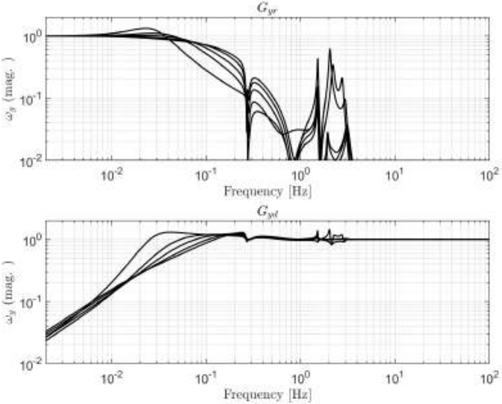
L(s):

$$-0.005\left(1+\frac{0.2}{s}\right)P(s)LP(s)$$

Pitch control: PI +

Reference tracking:

- $L(s)$
- Add LP $(1^{st}, 2^{nd})$
- Tune Gain
- Add I-action
- CL



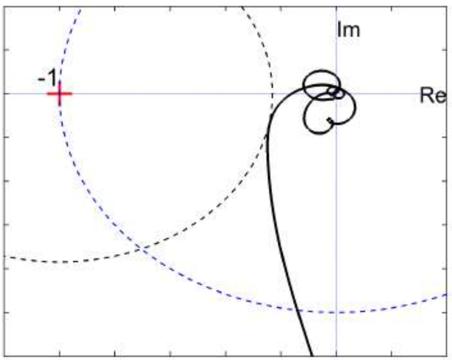
L(s):

$-0.005\left(1+\frac{0.2}{s}\right)P(s)LP(s)$

Pitch control: PI +

Reference tracking:

- $L(s)$
- Add LP $(1^{st}, 2^{nd})$
- Tune Gain
- Add I-action
- Nyquist



L(s):

$$-0.005\left(1+\frac{0.2}{s}\right)P(s)LP(s)$$

Pitch control: PI +

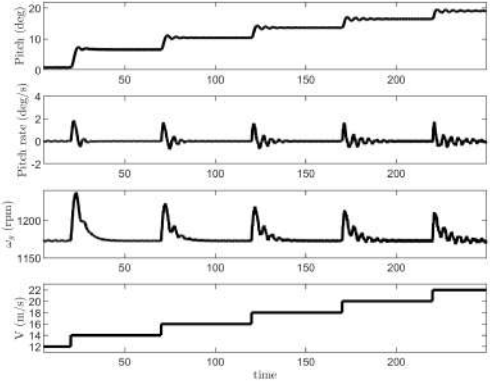
Reference tracking:

- $L(s)$
- Add LP $(1^{st}, 2^{nd})$
- Tune Gain
- Add I-action

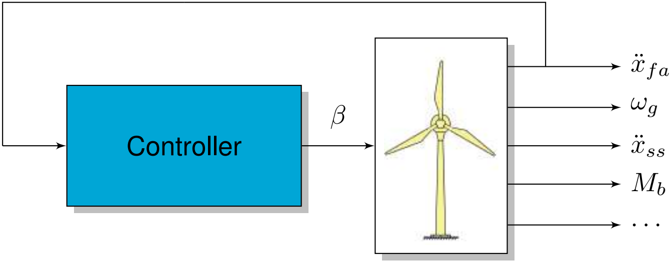
- Time Domain

L(s):

$$-0.005\left(1+\frac{0.2}{s}\right)P(s)LP(s)$$



Fore-aft tower damper



Fore-aft tower damping (the concept)

Tower dynamics (approx.):

$$M\ddot{x}_{fa} + D\dot{x}_{fa} + Kx_{fa} = F + \delta F$$

Typically, D small. Add damping by:

$$\delta F = -D_p \dot{x}_{fa}$$

Pitch will affect the thrust force (F):

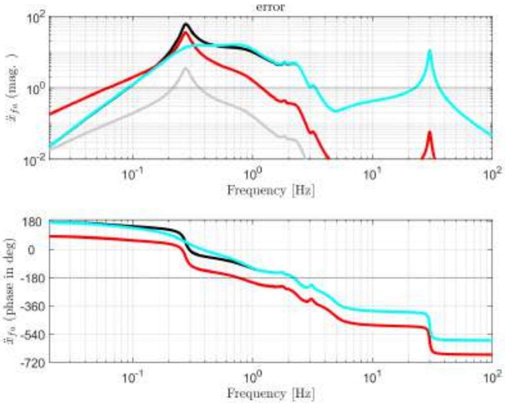
$$\delta F = \frac{\partial F}{\partial \beta}\delta\beta = -D_p\dot{x}_{fa} \quad \Longrightarrow \quad \delta\beta = \frac{-D_p}{\partial F/\partial\beta}\dot{x}_{fa}$$

How to pick this gain? (Use the loopshaping ideas)

Tower damper

Vibration control:

- P
- Integrate
- Tune Gain
- $\frac{P}{1+PC}$



OL:

$-0.1\frac{1}{s}P(s)$

Tower damper

Vibration control:

- Time Domain

OL:

$-0.1\frac{1}{s}P(s)$