Feedforward

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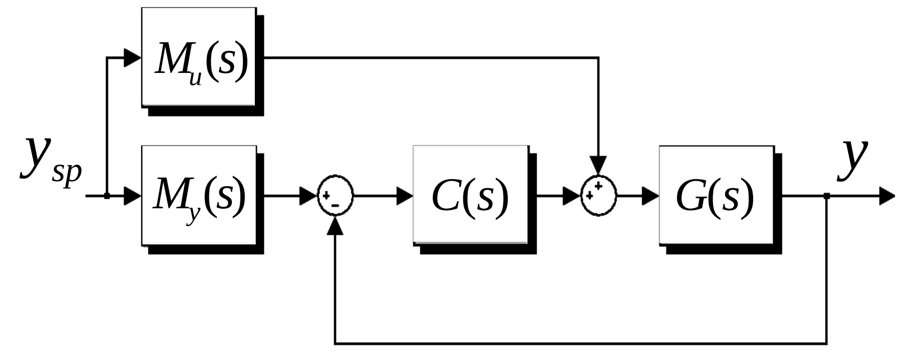
Automatic control 2012

Part I.
Reference signal.

FF & model matching (Astrom)

- Given: system G, designed feedback controller C, desired behavior My
- Goal: model matching:

$$T_{yy_{sp}} \cong M_y$$



$$T_{yy_{sp}} = \frac{G\left(CM_y + M_u\right)}{1+GC} = M_y + \frac{GM_u - M_y}{1+GC}$$

$1+GC$ large ➡ $T_{yy_{sp}} \approx M_y$

$GM_u = M_y$ ➡ $T_{yy_{sp}} = M_y$

$$\boxed{M_u = G^{-1}M_y}$$

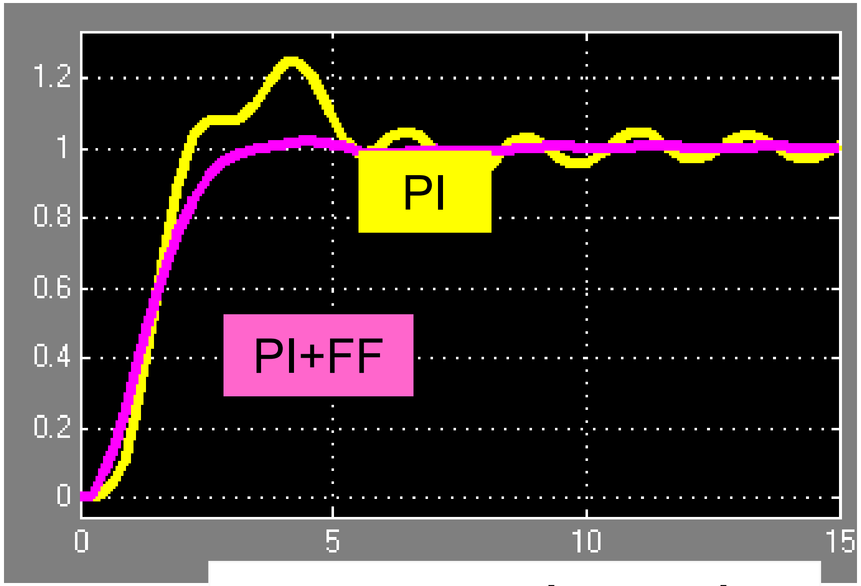
Example

G: $$G(s)=\frac{9}{(s+1)(s^2+0.1s+9)}$$

C: PI controller, $K=-0.167, T_i=-0.210$

My: $$M_y(s)=\frac{9}{(s+1)(s^2+6s+9)}$$

$$M_u(s)=\frac{s^2+0.1s+9}{s^2+6s+9}$$

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>> K=-.167,Ti=-.21,b=0
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Dynamics inversion

Get: $M_u = G^{-1} M_y$

But e.g. for:

$$G(s) = \frac{s-1}{s^2+4s+4} e^{-hs} \quad \Rightarrow \quad G^{-1}(s) = \frac{s^2+4s+4}{s-1} e^{hs}$$

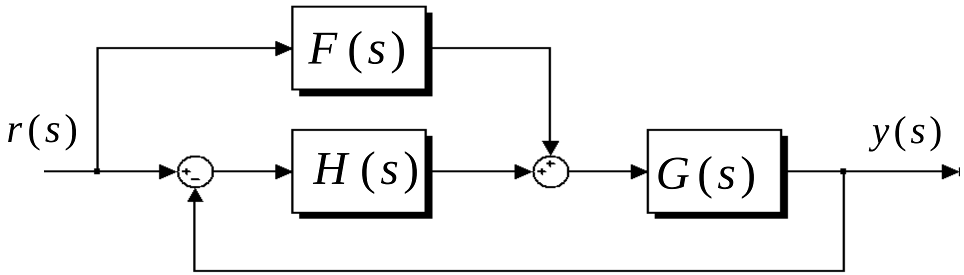
Therefore: inverse approximations $G^\dagger$, like:

$$G^\dagger(s) = G(0)^{-1}$$

$$G(s) = \frac{1}{1+sT} e^{-hs} \quad \Rightarrow \quad G^\dagger(s) = \frac{1+sT}{1+sT/N}$$

$$G(s) = \frac{s-1}{s+2} \quad \Rightarrow \quad G^\dagger(s) = \frac{s+2}{s+1}$$

FF & model matching: special case



$$y(s) = \frac{GH + GF}{1 + GH} r(s)$$

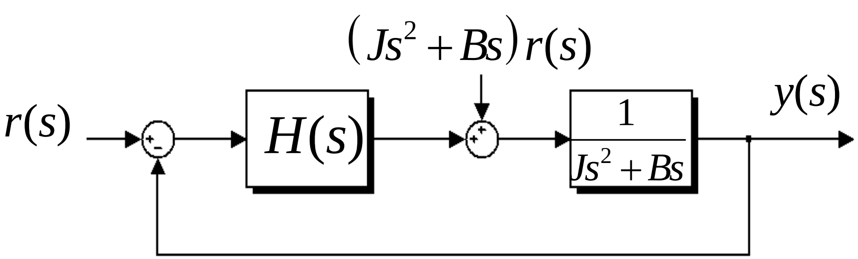
$$e(s) = r(s) - y(s)$$

$$= \frac{1 - GF}{1 + GH} r(s)$$

$$F(s) = G(s)^{-1} \Rightarrow e(s) = 0 \quad \forall r(s)$$

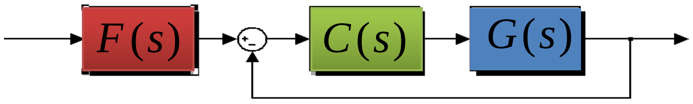
Example/application: robotics (manipulators' control systems, servos)

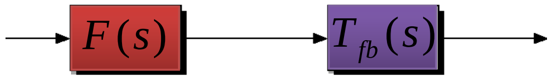
$$G(s) = \frac{1}{Js^2 + Bs} \Rightarrow F(s) = G(s)^{-1} = Js^2 + Bs$$



Zeros-dynamics compensation by pre-filter

$$T_{fb}(s) = \frac{C(s)G(s)}{1+C(s)G(s)} = \frac{b(s)q(s)}{a(s)p(s)+b(s)q(s)}$$





$$G(s) = \frac{b(s)}{a(s)}, C(s) = \frac{q(s)}{p(s)}, F(s) = \frac{r(s)}{t(s)}$$

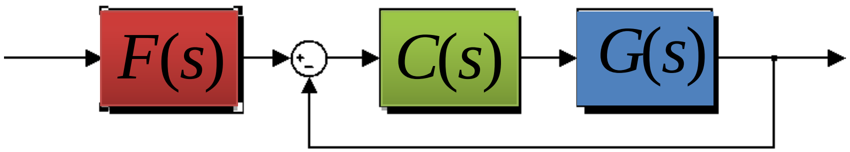
$$F(s) = \frac{k_F}{b(s)q(s)} \Rightarrow T(s) = \frac{C(s)G(s)F(s)}{1+C(s)G(s)} = \frac{k_F}{a(s)p(s)+b(s)q(s)}$$

$\left(F(s) = \frac{k_F}{b_{stab}(s)q_{stab}(s)} \right.$ for unstable numerator ...$\left. \right)$

Example

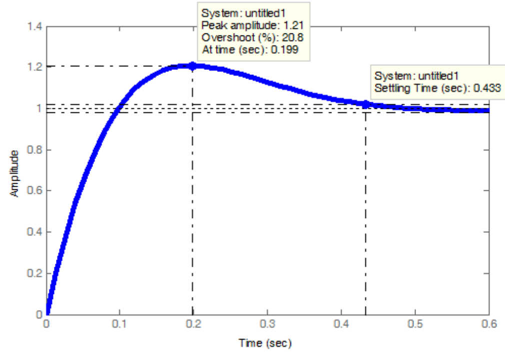
$$G(s)=\frac{1}{s}$$

$$C(s)=16+\frac{128}{s}=\frac{16(s+8)}{s}$$

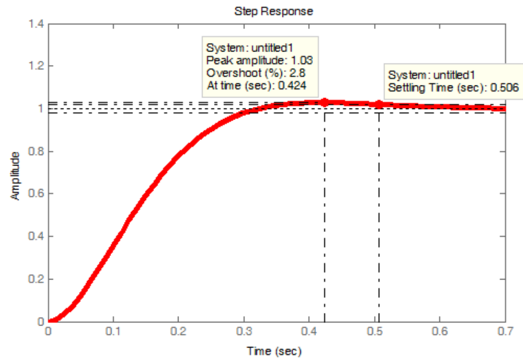


$$c(s)=s^2+16s+128$$

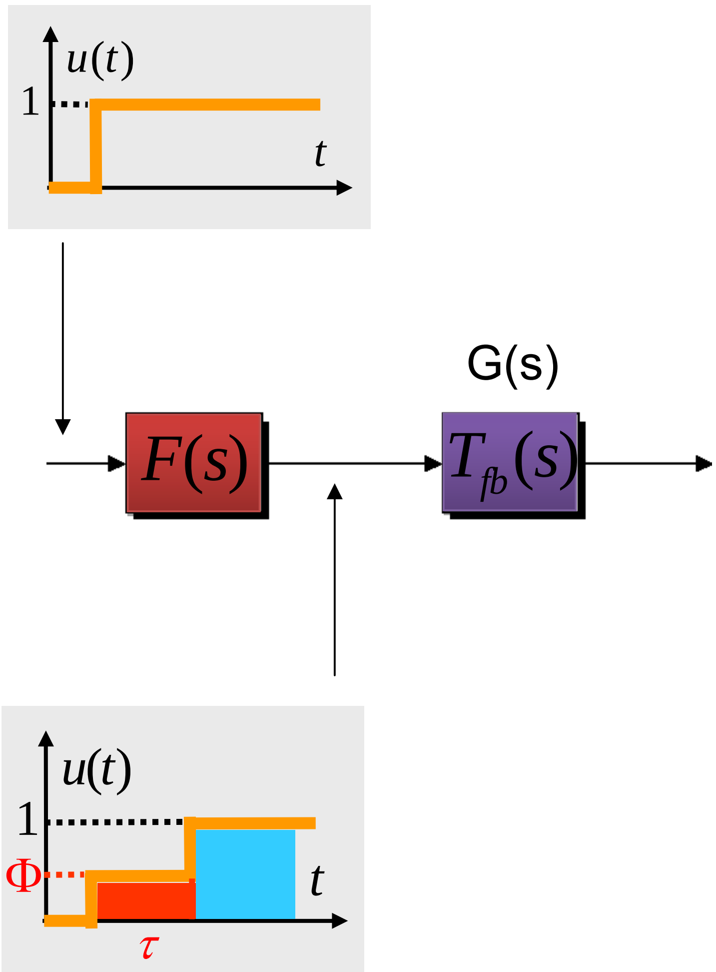
$$T_{fb}(s)=\frac{16(s+8)}{s^2+16s+128}$$

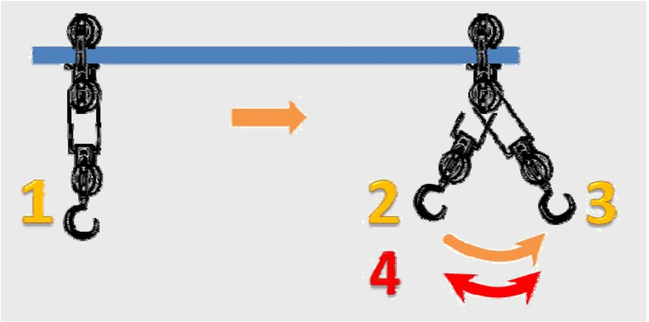


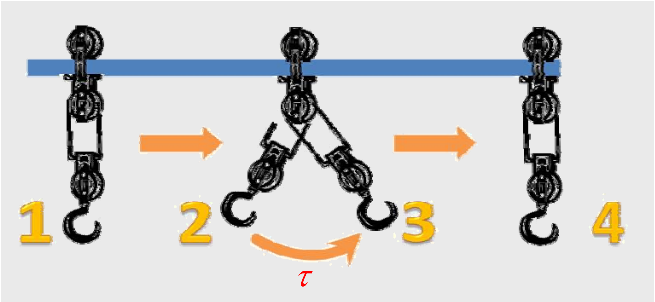
$$F(s)=\frac{8}{s+8} \Rightarrow T_{fb}(s)=\frac{128}{s^2+16s+128}$$



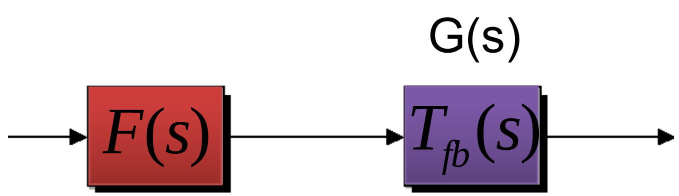
Input command shaping (PosiCast et.al.)







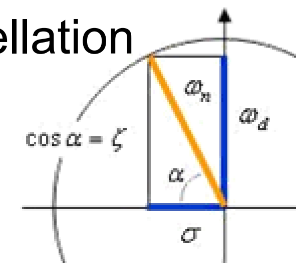
Design equations



$$G(s) = \frac{\omega_n^2}{s^2 + 2\omega_n \zeta s + \omega_n^2}$$

$$F(s) = \Phi + (1-\Phi)e^{-\tau s}, \quad \Phi \in [0,1]$$

principle = zero-pole cancellation



$$s_{1,2} = -\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2}$$

$$F(s_{1,2}) = F(-\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2}) = 0$$

$$\operatorname{Re} f(s_{1,2}) = \Phi + (1-\Phi)e^{\tau\zeta\omega_n}\cos\left(\tau\omega_n\sqrt{1-\zeta^2}\right) = 0$$

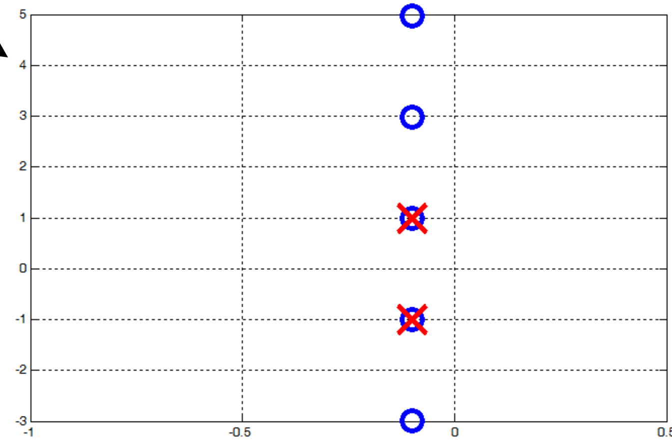
$$\operatorname{Im} f(s_{1,2}) = \pm(1-\Phi)e^{\tau\zeta\omega_n}\sin\left(\tau\omega_n\sqrt{1-\zeta^2}\right) = 0$$

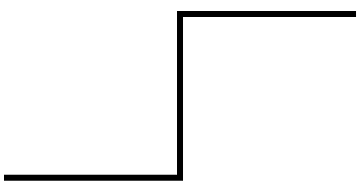
$$\tau = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}}$$

$$\Phi = \frac{1}{1+e^{-\tau\zeta\omega_n}} = \frac{1}{1+e^{-\frac{\pi}{\sqrt{1-\zeta^2}}\zeta}}$$

Zeros and poles. ZV, ZVD, EI shapers ...

PosiCast = ZV shaper





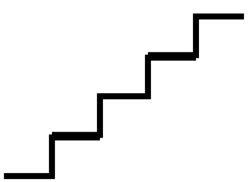
Further simple alternatives (patented):

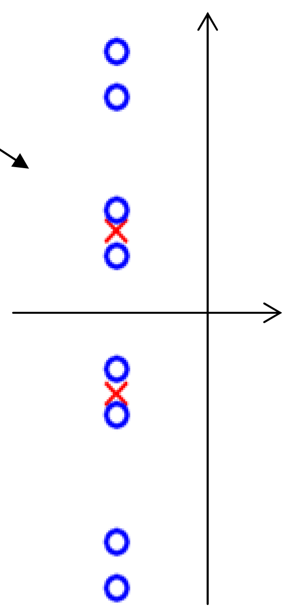
ZVD: 2 ZV’s (with same freq.) in series

EI: 2 “detuned” ZV’s

Two-hump: for two distinct modes

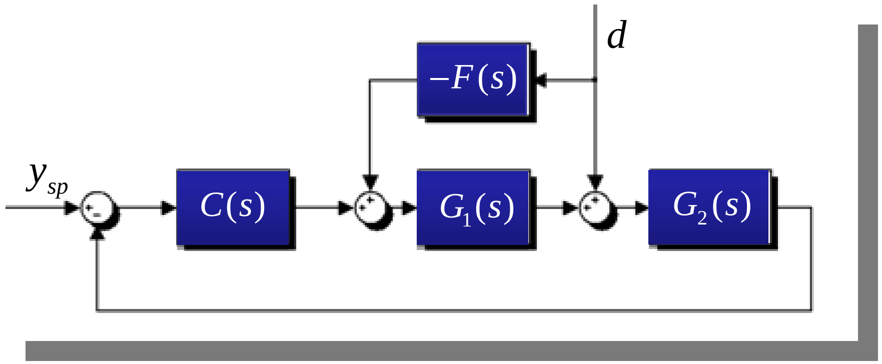
etc. ...





Part II.
Measured disturbance.

Disturbance feedforward



$$T_{yd}(s) = \frac{G_2\left(1 - G_1 F\right)}{1 + G_1 G_2 C} = G_2\left(1 - G_1 F\right) S$$

$$L(s) = G_1(s) G_2(s) C(s)$$

... large $S(s)$

... or $F(s) = G_1^{-1}(s)$ ⟹ $1 - G_1(s) F(s) = 0$

Part III.
Applications / Case studies.

-flexible aircraft gust load alleviation system

m-file (/Matlab/ARI_FF_alfaprobe)

presentation, ACFA 2020 (Dokumety/ARI.../Dop-ARI10... .pptx)

-flexible A/C two-channel feedforward LONG control

presentation, ACFA 2020 (Dokumety/ARI.../Dop-ARI10... .pptx)

-feedforward inversion of loudspeakers dynamics

link to identification / inversion of GSM communication channel ...

dissertation presentation, ACFA 2020 (Dokumenty/dizertacePrezentace)

-active echo cancellation / noise cancelling headphones

no materials, explain ...

-PosiCast vs. active damping feedback system for portal crane

video (Plocha/EUCASS Hromcik/Aktivni.avi, ZV.avi (PosiCast))

-PosiCast for manipulator with flexible load

video (Plocha/EUCASS Hromcik/ARIIS.avi)