ME 233 Advance Control II

Continuous-time results 5

Frequency-Shaped Linear Quadratic Regulator

(ME233 Class Notes pp.FSLQ1-FSLQ5)

Outline

- Parseval's theorem
- Frequency shaped LQR cost function
- Implementation

Infinite Horizon LQR

nth order LTI system:

$$\dot{x}(t) = A\,x(t) + B\,u(t) \qquad x(0) = x_o$$

Find the optimal control:

$$u(t) = -K\,x(t)$$

which minimizes the cost functional:

$$J = \frac{1}{2}\int_0^\infty \left\{x^T Q\,x + \rho\,u^T R\,u\right\}\,dt$$

$$Q = Q^T \succeq 0 \qquad R = R^T \succ 0 \quad \rho > 0$$

Parseval's theorem

- Let $f(t) : [0,\infty) \to \mathcal{R}^n$
- Its (symmetric) Fourier transform is defined by

$$F(j\omega) = \mathcal{F}(f(t)) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt$$

and

$$f(t) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} F(j\omega)e^{+j\omega t}d\omega$$

Parseval's theorem

$$\int_{-\infty}^{\infty} f^T(t) f(t) dt = \int_{-\infty}^{\infty} F^*(j\omega) F(j\omega) d\omega$$

where

$$F(j\omega) = \mathcal{F}(f(t))$$

$F^*(j\omega) = F^T(-j\omega)$ (complex conjugate transpose)

$$\int_{-\infty}^{\infty} f^T(t) f(t) dt = \int_{-\infty}^{\infty} F^*(j\omega) F(j\omega) d\omega$$

Proof:

$$\int_{-\infty}^{\infty} f^T(t) f(t) dt =$$

$$= \int_{-\infty}^{\infty} f^T(t) \overbrace{\left(\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F(j\omega) e^{+j\omega t} d\omega \right)}^{f(t)} dt$$

$$= \int_{-\infty}^{\infty} \underbrace{\left(\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f^T(t) e^{+j\omega t} dt \right)}_{F^T(-j\omega)} F(j\omega) d\omega$$

Frequency Cost Function

By Parseval's theorem, the cost functional:

$$J = \frac{1}{2} \int_{0}^{\infty} \left\{ x^T(t)\, Q\, x(t) + \rho\, u^T(t)\, R\, u(t) \right\} dt$$

with $\begin{cases} x(t) = 0 & t < 0 \\ u(t) = 0 & t < 0 \end{cases}$

is equivalent to

$$J = \frac{1}{2} \int_{-\infty}^{\infty} \{ X^*(j\omega)\, Q\, X(j\omega) + \rho\, U^*(j\omega)\, R\, U(j\omega) \}\, dw$$

$$X(j\omega) = \mathcal{F}(x(t)) \qquad U(j\omega) = \mathcal{F}(u(t))$$

Frequency-Shaped Cost Function

Key idea: Make matrices Q and R functions of frequency

$$J = \frac{1}{2} \int_{-\infty}^{\infty} \{ X^*(j\omega)\, Q(j\omega)\, X(j\omega)$$

$$+ \rho\, U^*(j\omega)\, R(j\omega)\, U(j\omega) \}\, d\omega$$

where

$$Q(j\omega) = Q_f^*(j\omega) Q_f(j\omega) \succeq 0$$

$$R(j\omega) = R_f^*(j\omega) R_f(j\omega) \succ 0$$

Frequency-Shaped Cost Function

Define the state and input filters

$$X(j\omega) \longrightarrow \underbrace{\boxed{Q_f(j\omega)}}_{\textit{state filter}} \longrightarrow X_f(j\omega)$$

$$U(j\omega) \longrightarrow \underbrace{\boxed{R_f(j\omega)}}_{\textit{input filter}} \longrightarrow U_f(j\omega)$$

Frequency-Shaped Cost Function

$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{X^*(j\omega)\underbrace{Q(j\omega)}_{Q_f^*(j\omega)Q_f(j\omega)}X(j\omega) + \rho\, U^*(j\omega)\underbrace{R(j\omega)}_{R_f^*(j\omega)R_f(j\omega)}U(j\omega)\}\, d\omega$$

can be written

$$J = \frac{1}{2}\int_{-\infty}^{\infty} \left\{X_f^*(j\omega)\, X_f(j\omega) + \rho U_f^*(j\omega)\, U_f(j\omega)\right\} d\omega$$

Realizing the filters using LTI's

$$X(j\omega) \longrightarrow \boxed{Q_f(j\omega)} \longrightarrow X_f(j\omega)$$

can be realized by

$$\dot{z}_1(t) = A_1\, z_1(t) + B_1\, x(t)$$
$$x_f(t) = C_1\, z_1(t) + D_1\, x(t)$$

so that

$$Q_f(s) = C_1(sI - A_1)^{-1}B_1 + D_1$$

is causal or strictly causal.

Realizing the filters using LTI's

$$U(j\omega) \longrightarrow \boxed{R_f(j\omega)} \longrightarrow U_f(j\omega)$$

can be realized by (with $D_2^T D_2 \succ 0$)

$$\dot{z}_2(t) = A_2\, z_2(t) + B_2\, u(t)$$
$$u_f(t) = C_2\, z_2(t) + D_2\, u(t)$$

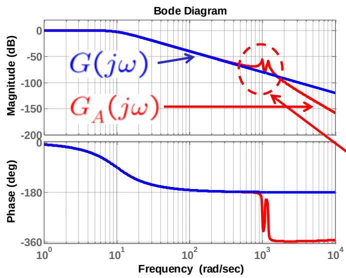
so that

$$R_f(s) = C_2(sI - A_2)^{-1}B_2 + D_2$$

is causal (but not strictly causal).

Example Hard Disk Drive

Consider a simplified model of a voice coil motor and suspension



$$G_A(s) = G(s)\,[1+\Delta(s)]$$

uncertainty

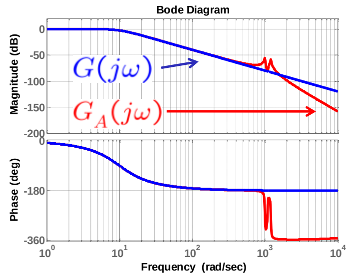
nominal model

actual plant

high-frequency resonance modes are neglected in the nominal model

nominal model $\quad G(s) = \dfrac{100}{s^2+14s+100}$

Example Hard Disk Drive



$$G_A(s) = G(s)\,[1+\Delta(s)]$$

uncertainty

nominal model

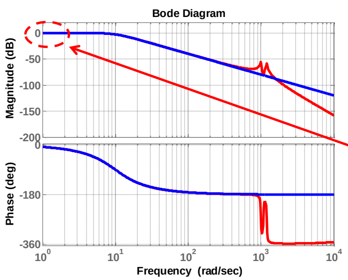
actual plant

nominal model

$$\frac{d}{dt}\begin{bmatrix} p \\ v \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -100 & -14 \end{bmatrix} \underbrace{\begin{bmatrix} p \\ v \end{bmatrix}}_{x(t)} + \begin{bmatrix} 1 \\ 100 \end{bmatrix} u$$

output is position $\quad y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} p \\ v \end{bmatrix}$

Example: Frequency State Weight Q(jω)



$$\frac{d}{dt}\begin{bmatrix} p \\ v \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -100 & -14 \end{bmatrix} \underbrace{\begin{bmatrix} p \\ v \end{bmatrix}}_{x(t)} + \begin{bmatrix} 1 \\ 100 \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} p \\ v \end{bmatrix}$$

we want zero steady state (i.e. dc) position

set position cost function weight to go to ∞ as $\omega \to 0$

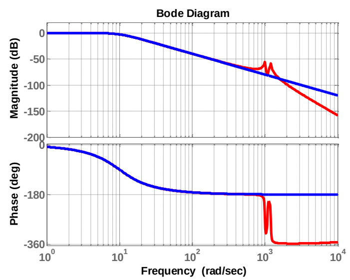
Example

Set weight on $|P(j\omega)|^2$ to $\dfrac{1}{\omega^2}$

Set weight on $|V(j\omega)|^2$ to 0

$$\underbrace{\begin{bmatrix} P(j\omega) \\ V(j\omega) \end{bmatrix}^*}_{X(j\omega)^*} \underbrace{\begin{bmatrix} \frac{1}{\omega^2} & 0 \\ 0 & 0 \end{bmatrix}}_{Q(j\omega)} \underbrace{\begin{bmatrix} P(j\omega) \\ V(j\omega) \end{bmatrix}}_{X(j\omega)}$$

Example: Frequency State Weight Q(jω)



$$\frac{d}{dt}\begin{bmatrix} p \\ v \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -100 & -14 \end{bmatrix} \underbrace{\begin{bmatrix} p \\ v \end{bmatrix}}_{x(t)} + \begin{bmatrix} 1 \\ 100 \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} p \\ v \end{bmatrix}$$

set position weight to go to ∞ as $\omega \to 0$

Example

$$\underbrace{\begin{bmatrix} P(j\omega) \\ V(j\omega) \end{bmatrix}^*}_{X(j\omega)^*} \underbrace{\begin{bmatrix} \frac{1}{\omega^2} & 0 \\ 0 & 0 \end{bmatrix}}_{Q(j\omega)} \underbrace{\begin{bmatrix} P(j\omega) \\ V(j\omega) \end{bmatrix}}_{X(j\omega)} = \underbrace{\underbrace{\begin{bmatrix} P(j\omega) \\ V(j\omega) \end{bmatrix}^*}_{X(j\omega)^*} \underbrace{\begin{bmatrix} \frac{-1}{j\omega} \\ 0 \end{bmatrix}}_{Q_f(j\omega)^*}}_{X_f(j\omega)^*} \underbrace{\underbrace{\begin{bmatrix} \frac{1}{j\omega} & 0 \end{bmatrix}}_{Q_f(j\omega)} \underbrace{\begin{bmatrix} P(j\omega) \\ V(j\omega) \end{bmatrix}}_{X(j\omega)}}_{X_f(j\omega)}$$

Example: Frequency State Weight Q(jω)

$$X(j\omega) \longrightarrow \boxed{Q_f(j\omega)} \longrightarrow X_f(j\omega)$$

state space realization

$$\begin{aligned} \dot z_1(t) &= A_1\, z_1(t) + B_1\, x(t) \\ x_f(t) &= C_1\, z_1(t) + D_1\, x(t) \end{aligned}$$

Example

$$X(f) = \underbrace{\begin{bmatrix} \frac{1}{j\omega} & 0 \end{bmatrix}}_{Q_f(j\omega)} X(j\omega)$$

state space realization

$$Q_f(j\omega) = \begin{bmatrix} \frac{1}{j\omega} & 0 \end{bmatrix} \Rightarrow \begin{cases} \frac{d}{dt} z_1(t) = \underbrace{0}_{A_1}\, z_1(t) + \underbrace{\begin{bmatrix} 1 & 0 \end{bmatrix}}_{B_1} x(t) \\ x_f(t) = \underbrace{1}_{C_1}\, z_1(t) + \underbrace{\begin{bmatrix} 0 & 0 \end{bmatrix}}_{D_1} x(t) \end{cases}$$

Example Hard Disk Drive

$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{X^*(j\omega)\, Q(j\omega)\, X(j\omega) + \rho\, U^*(j\omega)\; U(j\omega)\}\, d\omega$$

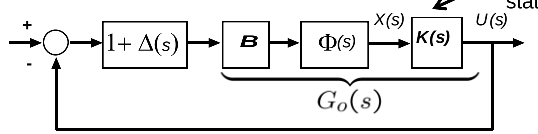
nominal model

weights: $Q(j\omega) = \begin{bmatrix} \frac{1}{\omega^2} & 0 \\ 0 & 0 \end{bmatrix}$

$$\frac{d}{dt}\begin{bmatrix} p \\ v \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -100 & -14 \end{bmatrix}\begin{bmatrix} p \\ v \end{bmatrix} + \begin{bmatrix} 1 \\ 100 \end{bmatrix} u$$

$\rho \approx 1.6E-8$

FS-LQR is a dynamic state feedback

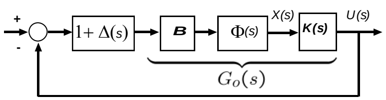


sufficient condition for robustness

$$T(s) = \frac{G_o(s)}{1 + G_o(s)} \qquad |T(j\omega)| \le \frac{1}{|\Delta(j\omega)|}$$

Example Hard Disk Drive

$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{X^*(j\omega)\, Q(j\omega)\, X(j\omega) + \rho\, U^*(j\omega)\; U(j\omega)\}\, d\omega$$

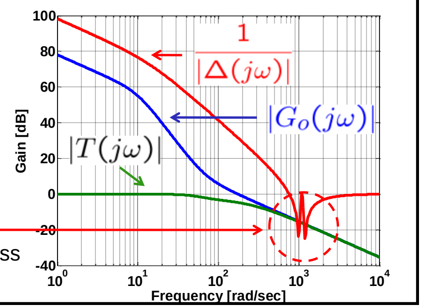


weights: $Q(j\omega) = \begin{bmatrix} \frac{1}{\omega^2} & 0 \\ 0 & 0 \end{bmatrix}$

$\rho \approx 1.6E-8$

$$T(s) = \frac{G_o(s)}{1 + G_o(s)}$$

potential
lack of robustness

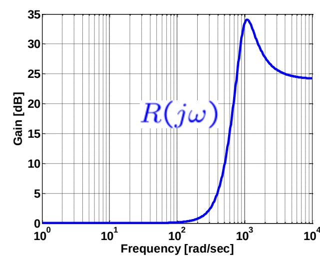


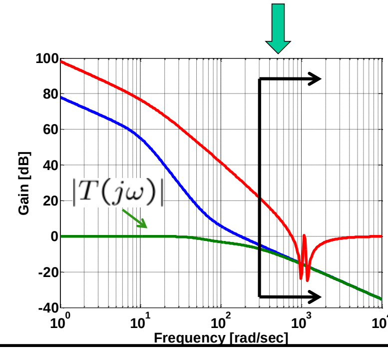
Example: Frequency Control Weight R(jω)

$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{X^*(j\omega)\, Q(j\omega)\, X(j\omega) + \rho\, U^*(j\omega)\, \underbrace{R(j\omega)}\, U(j\omega)\}\, d\omega$$

increase control penalty
at high-frequencies

Example

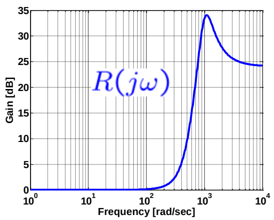




Example: Frequency Control Weight R(jω)

$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{X^*(j\omega)\,Q(j\omega)\,X(j\omega) + \rho\,\underbrace{U^*(j\omega)\,R(j\omega)\,U(j\omega)}_{U_f^*(j\omega)U_f(j\omega)}\}\,d\omega$$

Example



$$R(j\omega) = R_f^*(j\omega)\,R_f(j\omega)$$

$$R_f(j\omega) = 4\frac{s^2 + 700s + (500)^2}{s^2 + 600s + (1000)^2}$$

state space realization

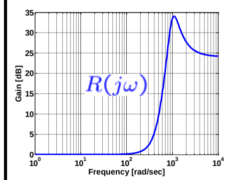
$$U(j\omega) \longrightarrow \boxed{R_f(j\omega)} \longrightarrow U_f(j\omega)$$

$$\begin{cases} \dfrac{d}{dt}z_2 = \underbrace{\begin{bmatrix} -600 & -980 \\ -100 & 0 \end{bmatrix}}_{A_2} z_2 + \underbrace{\begin{bmatrix} 64 \\ 0 \end{bmatrix}}_{B_2} u \\ u_f = \underbrace{\begin{bmatrix} 6.3 & -46 \end{bmatrix}}_{C_2} z_2 + \underbrace{4}_{D_2}\,u \end{cases}$$

Example: Frequency Control Weight R(jω)

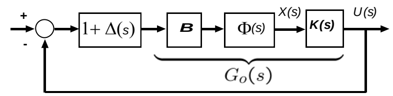
$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{X^*(j\omega)\,Q(j\omega)\,X(j\omega) + \rho\,U^*(j\omega)\,R(j\omega)\,U(j\omega)\}\,d\omega$$

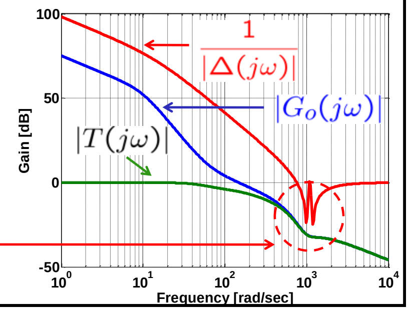
Example



$$Q(j\omega) = \begin{bmatrix} \frac{1}{\omega^2} & 0 \\ 0 & 0 \end{bmatrix}$$

$$\rho \approx 1.6E-8$$





sufficient robustness condition is satisfied

Cost Function Realization

$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{X^*(j\omega)\,Q(j\omega)\,X(j\omega) + \rho\,U^*(j\omega)\,R(j\omega)\,U(j\omega)\}\,d\omega$$

is equivalent to

$$J \;=\; \frac{1}{2}\int_0^{\infty} \left\{x_f^T(t)\,x_f(t) \;+\; \rho\,u_f^T(t)\;u_f(t)\right\}dt$$

Cost Function Realization

$$J \;=\; \frac{1}{2}\int_0^{\infty} \left\{x_f^T(t)\,x_f(t) \;+\; \rho\,u_f^T(t)\;u_f(t)\right\}dt$$

we know that,

$$X(j\omega) \longrightarrow \boxed{Q_f(j\omega)} \longrightarrow X_f(j\omega)$$

state space realization

$$\begin{aligned} \dot z_1(t) &= A_1\,z_1(t) + B_1\,x(t) \\ x_f(t) &= C_1\,z_1(t) + D_1\,x(t) \end{aligned}$$

$$U(j\omega) \longrightarrow \boxed{R_f(j\omega)} \longrightarrow U_f(j\omega)$$

state space realization

$$\begin{aligned} \dot z_2(t) &= A_2\,z_2(t) + B_2\,u(t) \\ u_f(t) &= C_2\,z_2(t) + D_2\,u(t) \end{aligned}$$

25

Cost Function Realization

$$J = \frac{1}{2}\int_0^\infty \left\{ x_f^T(t)\, x_f(t) + \rho\, u_f^T(t)\, u_f(t) \right\} dt$$

$$\dot{z}_1(t) = A_1 z_1(t) + B_1 x(t) \qquad \dot{z}_2(t) = A_2 z_2(t) + B_2 u(t)$$

$$x_f(t) = C_1 z_1(t) + D_1 x(t) \qquad u_f(t) = C_2 z_2(t) + D_2 u(t)$$

Plus: $\dot{x}(t) = A\, x(t) + B\, u(t)$

define extended state $x_e(t) = \begin{bmatrix} x(t) \\ z_1(t) \\ z_2(t) \end{bmatrix}$

26

Cost Function Realization

$$J = \frac{1}{2}\int_0^\infty \left\{ x_f^T(t)\, x_f(t) + \rho\, u_f^T(t)\, u_f(t) \right\} dt$$

We can combine state equations and output as follows:

$$\frac{d}{dt}\begin{bmatrix} x \\ z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} A & 0 & 0 \\ B_1 & A_1 & 0 \\ 0 & 0 & A_2 \end{bmatrix}\begin{bmatrix} x \\ z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} B \\ 0 \\ B_2 \end{bmatrix} u$$

$$\begin{bmatrix} x_f \\ u_f \end{bmatrix} = \begin{bmatrix} D_1 & C_1 & 0 \\ 0 & 0 & C_2 \end{bmatrix}\begin{bmatrix} x \\ z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ D_2 \end{bmatrix} u$$

27

Extended System Dynamics

$$\underbrace{\frac{d}{dt}\begin{bmatrix} x \\ z_1 \\ z_2 \end{bmatrix}}_{x_e} = \underbrace{\begin{bmatrix} A & 0 & 0 \\ B_1 & A_1 & 0 \\ 0 & 0 & A_2 \end{bmatrix}}_{A_e}\underbrace{\begin{bmatrix} x \\ z_1 \\ z_2 \end{bmatrix}}_{x_e} + \underbrace{\begin{bmatrix} B \\ 0 \\ B_2 \end{bmatrix}}_{B_e} u$$

$$\dot{x}_e(t) = A_e\, x_e(t) + B_e\, u(t)$$

28

Extended System Cost

$$J = \frac{1}{2}\int_0^\infty \left\{ x_f^T(t)\, x_f(t) + u_{ff}^T(t)\, u_{ff}(t) \right\} dt$$

$$\begin{bmatrix} x_f \\ u_{ff} \end{bmatrix} = \underbrace{\begin{bmatrix} D_1 & C_1 & 0 \\ 0 & 0 & \sqrt{\rho}C_2 \end{bmatrix}}_{C_e}\underbrace{\begin{bmatrix} x \\ z_1 \\ z_2 \end{bmatrix}}_{x_e} + \underbrace{\begin{bmatrix} 0 \\ \sqrt{\rho}D_2 \end{bmatrix}}_{D_e} u$$

results in

$$J = \frac{1}{2}\int_0^\infty \left\{ x_e^T C_e^T C_e x_e + 2\, x_e^T C_e^T D_e u + u^T D_e^T D_e u \right\} dt$$

Extended System Cost

$$J = \frac{1}{2}\int_0^\infty \left\{ x_e^T \underbrace{C_e^T C_e}_{Q_e} x_e + 2\, x_e^T \underbrace{C_e^T D_e}_{N_e} u + u^T \underbrace{D_e^T D_e}_{R_e} u \right\} dt$$

where

$$Q_e = \begin{bmatrix} D_1^T & 0 \\ C_1^T & 0 \\ 0 & \sqrt{\rho} C_2^T \end{bmatrix} \begin{bmatrix} D_1 & C_1 & 0 \\ 0 & 0 & \sqrt{\rho} C_2 \end{bmatrix}$$

$$N_e = \begin{bmatrix} D_1^T & 0 \\ C_1^T & 0 \\ 0 & \sqrt{\rho} C_2^T \end{bmatrix} \begin{bmatrix} 0 \\ \sqrt{\rho} D_2 \end{bmatrix} \qquad R_e = \begin{bmatrix} 0 & \sqrt{\rho} D_2^T \end{bmatrix} \begin{bmatrix} 0 \\ \sqrt{\rho} D_2 \end{bmatrix}$$

Extended System Cost

$$J = \frac{1}{2}\int_0^\infty \left\{ x_e^T Q_e x_e + 2\, x_e^T N_e u + u^T R_e u \right\} dt$$

where

$$Q_e = \begin{bmatrix} D_1^T D_1 & D_1^T C_1 & 0 \\ C_1^T D_1 & C_1^T C_1 & 0 \\ 0 & 0 & \rho C_2^T C_2 \end{bmatrix} \qquad N_e = \begin{bmatrix} 0 \\ 0 \\ \rho C_2^T D_2 \end{bmatrix}$$

$$R_e = \rho D_2^T D_2 \succ 0$$

Extended System LQR

Given the extended dynamics

$$\dot{x}_e(t) = A_e x_e(t) + B_e u(t)$$

Find the optimal control:

$$u(t) = -K_e x_e(t)$$

which minimizes the cost extended functional:

$$J = \frac{1}{2}\int_0^\infty \left\{ x_e^T Q_e x_e + 2\, x_e^T N_e u + u^T R_e u \right\} dt$$

Extended LQR Solution

$$\dot{x}_e(t) = A_e x_e(t) + B_e u(t)$$

$$J = \frac{1}{2}\int_0^\infty \left\{ x_e^T \underbrace{C_e^T C_e}_{Q_e} x_e + 2\, x_e^T N_e u + \rho u^T D_2^T D_2 u \right\} dt$$

where

$$\rho D_2^T D_2 \succ 0 \qquad C_e = \begin{bmatrix} D_1 & C_1 & 0 \\ 0 & 0 & \sqrt{\rho} C_2 \end{bmatrix} = \begin{bmatrix} C_q & \\ 0 \;\; 0 & \sqrt{\rho} C_2 \end{bmatrix}$$

Then

$[A_e, B_e]$ is stabilizable

$[A_e - B_e R_e^{-1} N_e^T, C_q]$ is detectable

$\Longleftrightarrow$

There exists a stabilizing optimal control shown in the next page

33

Extended LQR Solution

Optimal Control:

$$u(t) \;=\; -K_e\, x_e(t)$$

where

$$K_e = R_e^{-1}\left[B_e^T P_e + N_e^T\right]$$

and

$$P_e A_e + A_e^T P_e + Q_e$$

$$-\left[B_e^T P_e + N_e^T\right]^T R_e^{-1}\left[B_e^T P_e + N_e^T\right] = 0$$

34

Implementation

- Control

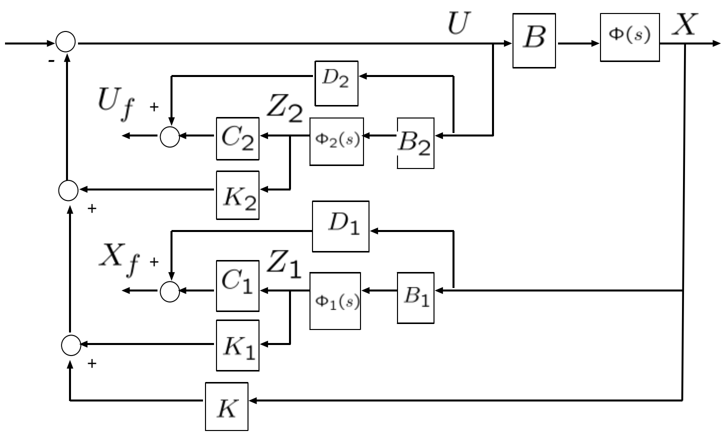
$$u(t) \;=\; -K_e\, x_e(t)$$

$$u(t) \;=\; -\begin{bmatrix} K & K_1 & K_2 \end{bmatrix}\begin{bmatrix} x(t) \\ z_1(t) \\ z_2(t) \end{bmatrix}$$

$$u(t) \;=\; -K\,x(t) - K_1\,z_1(t) - K_2\,z_2(t)$$

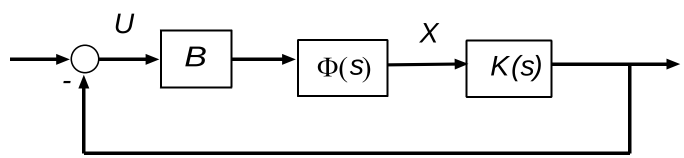
35

Block Diagram



36

Equivalent Block Diagram



$$K(s) = \left[I + K_2\Phi_2(s)B_2\right]^{-1}\left[K + K_1\Phi_1(s)B_1\right]$$

FSLQR with reference input

- For simplicity, lets assume a scalar output

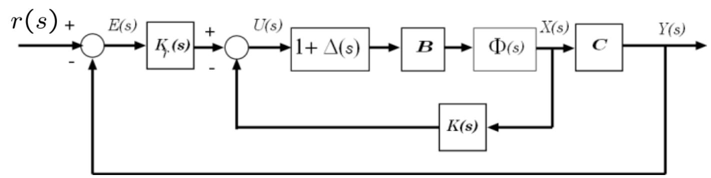
$$y(t) = Cx(t) \qquad y \in \mathcal{R}$$

- Assume that we want to design a FSLQR that will achieve asymptotic output convergence to a reference input

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

$$\lim_{t \to \infty} e(t) = 0$$

FSLQR with reference input



- Assume that the reference input *r(s)* satisfies

$$r(s) = \frac{\bar{B}_r(s)}{A_r(s)}$$

- Where $A_r(s)$ has root in the imaginary axis

Reference input examples

- Assume that $r(t) = r_o$

$$r(s) = \frac{1}{s} r_o \quad \Rightarrow \quad A_r(s) = s$$

- Assume that $r(t) = r_o \sin(\omega_r t)$

$$r(s) = \frac{\omega_r^2}{s^2 + \omega_r^2} r_o \quad \Rightarrow \quad A_r(s) = s^2 + \omega_r^2$$

FSLQR with reference input

- Define the reference frequency weight

$$Q_R(j\omega) = Q_r^*(j\omega) Q_r(j\omega) \succeq 0$$

- Where

$$Q_r(s) = \frac{B_r(s)}{A_r(s)}$$

$\boxed{A_r(s) \text{ is the denominator of } r(s)}$

$$r(s) = \frac{\bar{B}_r(s)}{A_r(s)}$$

41

Frequency-Shaped Cost Function

$$J \;=\; \frac{1}{2}\int_{-\infty}^{\infty} \{X^*(j\omega)\,Q(j\omega)\,X(j\omega)$$
$$+\;\rho\;U^*(j\omega)\,R(j\omega)\,U(j\omega)\}\;d\omega$$

- with

$$Q(j\omega) = \underbrace{C^T Q_r^*(j\omega) Q_r(j\omega) C}_{} + Q_f^*(j\omega) Q_f(j\omega)$$

used for achieving $\lim_{t\to\infty} e(t) = 0$

42

Frequency-Shaped Cost Function

$$J \;=\; \frac{1}{2}\int_{-\infty}^{\infty} \{X^*(j\omega)\,Q(j\omega)\,X(j\omega)$$
$$+\;\rho\;U^*(j\omega)\,R(j\omega)\,U(j\omega)\}\;d\omega$$

$$J \;=\; \frac{1}{2}\int_{-\infty}^{\infty} \Big\{Y_r^*(j\omega)\,Y_r(j\omega) + X_f^*(j\omega)\,X_f(j\omega)$$
$$+\;\rho\, U_f^*(j\omega)\;U_f(j\omega)\Big\}\;d\omega$$

43

Realizing the filters using LTI's

$$Y(j\omega) \longrightarrow \boxed{Q_r(j\omega)} \longrightarrow Y_r(j\omega)$$

can be realized by

$$\begin{aligned} \dot z_r(t) &= A_r\, z_r(t) + B_r\, y(t) \\ x_r(t) &= C_r\, z_r(t) + D_r y(t) \end{aligned}$$

such that

$$Q_r(s) = C_r(sI - A_r)^{-1}B_r + D_r \;=\; \frac{B_r(s)}{A_r(s)}$$

denominator of *r(s)*

44

Realizing the filters using LTI's

$$X(j\omega) \longrightarrow \boxed{Q_f(j\omega)} \longrightarrow X_f(j\omega)$$

can be realized by

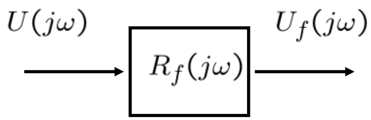
$$\begin{aligned} \dot z_1(t) &= A_1\, z_1(t) + B_1\, x(t) \\ x_f(t) &= C_1\, z_1(t) + D_1\, x(t) \end{aligned}$$

such that

$$Q_f(s) = C_1(sI - A_1)^{-1}B_1 + D_1$$

45

Realizing the filters using LTI’s



can be realized by

$$\begin{aligned} \dot{z}_2(t) &= A_2\, z_2(t) + B_2\, u(t) \\ u_f(t) &= C_2\, z_2(t) + D_2\, u(t) \end{aligned}$$

such that

$$R_f(s) = C_2(sI - A_2)^{-1}B_2 + D_2$$

46

Cost Function Realization

$$\begin{aligned} J &= \frac{1}{2}\int_{-\infty}^{\infty} \left\{ y_r^T(t)\, y_r(t) + x_f^T(t)\, x_f(t) \right. \\ & \qquad \left. +\ \rho\, u_f^T(t)\ u_f(t) \right\} dt \end{aligned}$$

where,

$$\frac{d}{dt}\begin{bmatrix} x \\ z_r \\ z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} A & 0 & 0 & 0 \\ B_rC & A_r & 0 & 0 \\ B_1 & 0 & A_1 & 0 \\ 0 & 0 & 0 & A_2 \end{bmatrix} \begin{bmatrix} x \\ z_r \\ z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} B \\ 0 \\ 0 \\ B_2 \end{bmatrix} u$$

$$\begin{bmatrix} y_r \\ x_f \\ u_f \end{bmatrix} = \begin{bmatrix} D_rC & C_r & 0 & 0 \\ D_1 & 0 & C_1 & 0 \\ 0 & 0 & 0 & C_2 \end{bmatrix} \begin{bmatrix} x \\ z_r \\ z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ D_2 \end{bmatrix} u$$

47

Extended System Dynamics

$$\frac{d}{dt}\underbrace{\begin{bmatrix} x \\ z_r \\ z_1 \\ z_2 \end{bmatrix}}_{x_e} = \underbrace{\begin{bmatrix} A & 0 & 0 & 0 \\ B_rC & A_r & 0 & 0 \\ B_1 & 0 & A_1 & 0 \\ 0 & 0 & 0 & A_2 \end{bmatrix}}_{A_e} \underbrace{\begin{bmatrix} x \\ z_r \\ z_1 \\ z_2 \end{bmatrix}}_{x_e} + \underbrace{\begin{bmatrix} B \\ 0 \\ 0 \\ B_2 \end{bmatrix}}_{B_e} u$$

$$\dot{x}_e(t) = A_e\, x_e(t) + B_e\, u(t)$$

48

Extended System Cost

$$J = \frac{1}{2}\int_{-\infty}^{\infty} \left\{ x_e^T\, Q_e\, x_e + 2\ x_e^T\, N_e\, u +\ u^T\, R_e\, u \right\} dt$$

$$Q_e = \begin{bmatrix} C^TD_r^T & D_1^T & 0 \\ C_r^T & 0 & 0 \\ 0 & C_1^T & 0 \\ 0 & 0 & \sqrt{\rho}C_2^T \end{bmatrix} \begin{bmatrix} D_rC & C_r & 0 & 0 \\ D_1 & 0 & C_1 & 0 \\ 0 & 0 & 0 & \sqrt{\rho}C_2 \end{bmatrix}$$

$$N_e = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \rho C_2^T D_2 \end{bmatrix} \qquad R_e = \rho D_2^T D2$$

49

Extended LQR Solution

$$\dot{x}_e(t) \;=\; A_e\, x_e(t) + B_e\, u(t)$$

$$J \;=\; \frac{1}{2}\int_0^\infty \Big\{ x_e^T \underbrace{C_e^T C_e}_{Q_e} x_e + 2\; x_e^T\, N_e\, u + \;\rho u^T\, D_2^T D_2\, u \Big\}\, dt$$

where

$$\rho\, D_2^T D_2 \succ 0 \qquad C_e \;=\; \begin{bmatrix} D_r C & C_r & 0 & 0 \\ D_1 & 0 & C_1 & 0 \\ 0 & 0 & 0 & \sqrt{\rho} C_2 \end{bmatrix} = \begin{bmatrix} & C_q & & \\ 0 & 0 & 0 & \sqrt{\rho} C_2 \end{bmatrix}$$

Then

$[A_e, B_e]$ is stabilizable

$[A_e - B_e R_e^{-1} N_e^T, C_q]$ is detectable

$\Longleftrightarrow$

There exists a stabilizing optimal control shown in the next page

50

Extended LQR Solution

Optimal Control Gain:

$$K_e = R_e^{-1}\left[B_e^T P_e + N_e^T\right]$$

where

$$P_e A_e + A_e^T P_e + Q_e$$

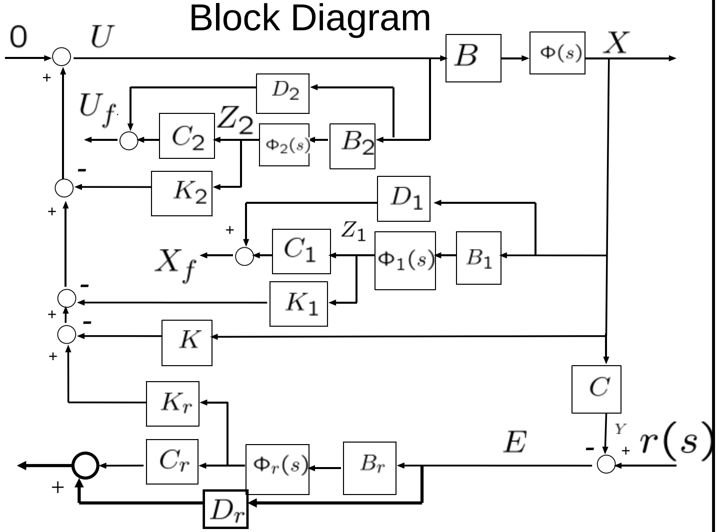
$$- \left[B_e^T P_e + N_e^T\right]^T R_e^{-1}\left[B_e^T P_e + N_e^T\right] = 0$$

and

$$K_e = \begin{bmatrix} K & K_r & K_1 & K_2 \end{bmatrix}$$

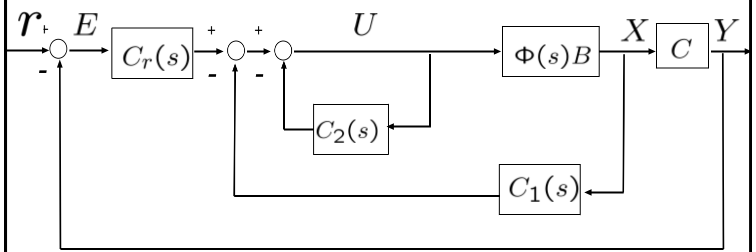
51

Block Diagram



52

FSLQR with reference input – Block Diagram

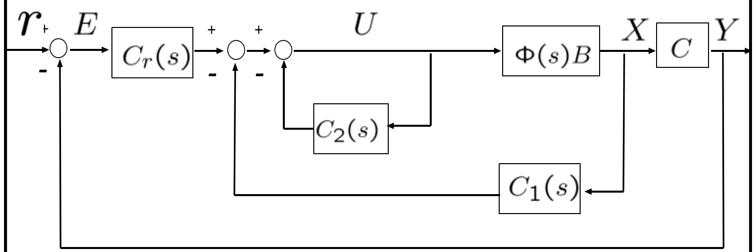


where

$$C_r(s) = K_r \Phi_r(s) B_r \qquad C_2(s) = K_2 \Phi_2(s) B_2$$

$$C_1(s) = K + K_1 \Phi_1(s) B_1$$

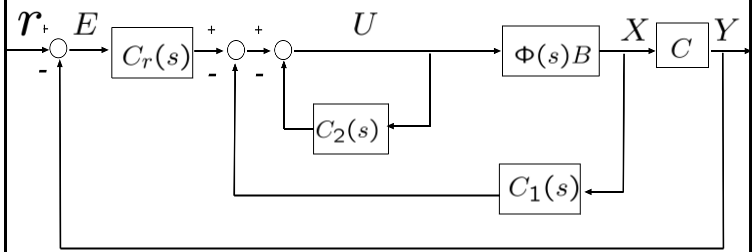
Block Diagram



Remember that the poles of $C_r(s)$ are $A_r(s)$, and

$$r(s) = \frac{B_r(s)}{A_r(s)}$$

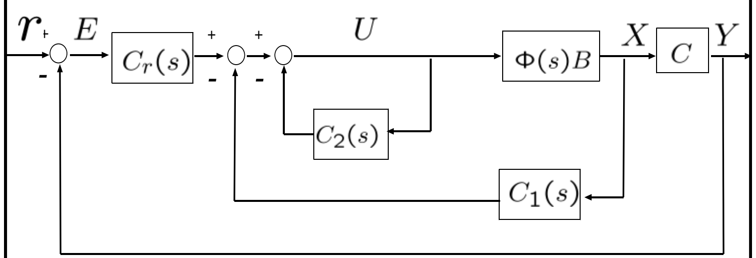
SISO



The close loop dynamics from $r(s)$ to $E(s)$ will be of the form

$$E(s) = \frac{B_c'(s)A_r(s)}{A_c(s)} r(s) \qquad r(s) = \frac{B_r(s)}{A_r(s)}$$

SISO

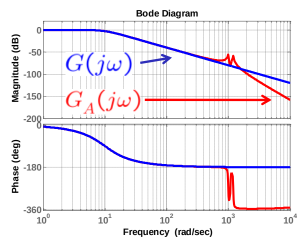


Therefore, since $A_c(s)$ is Hurwitz,

$$E(s) = \frac{B_c'(s)B_r(s)}{A_c(s)} \qquad \lim_{s\to 0} sE(s) = 0 \qquad \lim_{t\to\infty} e(t) = 0$$

Example Hard Disk Drive

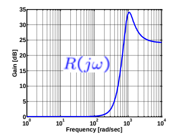
$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{Y^*(j\omega)Q_r(j\omega)Y(j\omega) + \rho\, u^*(j\omega)R(j\omega)u(j\omega)\}\, d\omega$$



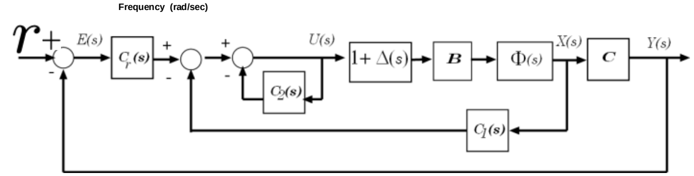
Cost weights:

$$Q_r(j\omega) = \frac{1}{\omega^2}$$

$$\rho \approx 1.6E-8$$



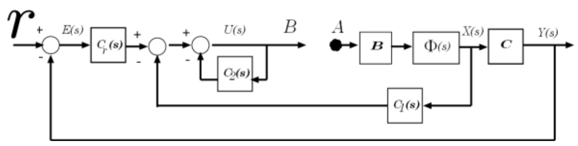
$$r(s) = \frac{r_o}{s}$$ reference input



57

Example Hard Disk Drive – Robustness Analysis

$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{Y^*(j\omega)Q_r(j\omega)Y(j\omega) + \rho u^*(j\omega)R(j\omega)u(j\omega)\}\, d\omega$$



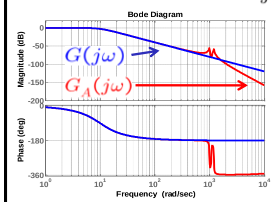
$$G_o(s) = \frac{A(s)}{B(s)} \qquad G_o(s) = \frac{[C_r(s)C + C_1(s)]\ \Phi(s)B}{1 + C_2(s)}$$

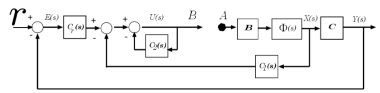
$$T(s) = \frac{G_o(s)}{1 + G_o(s)}$$

58

Example Hard Disk Drive

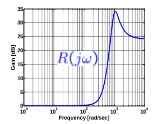
$$J = \frac{1}{2}\int_{-\infty}^{\infty} \{Y^*(j\omega)Q_r(j\omega)Y(j\omega) + \rho u^*(j\omega)R(j\omega)u(j\omega)\}\, d\omega$$

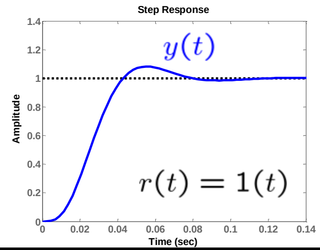


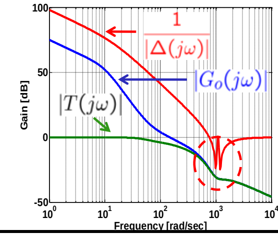


$$Q_r(j\omega) = \frac{1}{\omega^2}$$

$$\rho \approx 1.6E-8$$

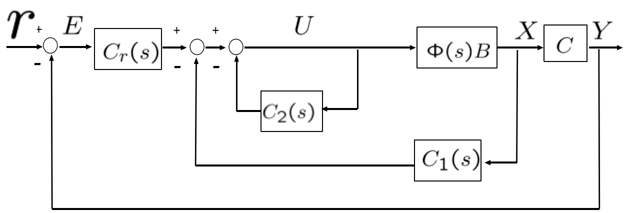






59

FSLQR with reference input – State Estimation



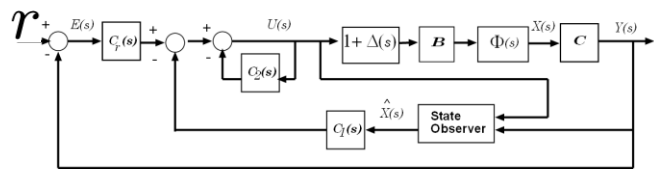
Assume that :

- state $x(t)$ is not measurable
- only output $y(t)$ is available

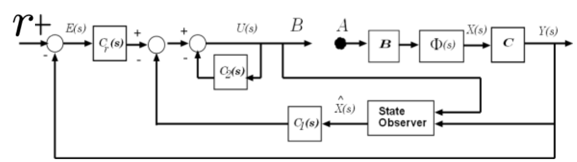
Use state observer

60

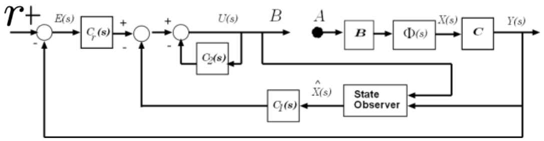
FSLQR with reference input – State Estimation



Robustness analysis:



Loop Transfer Recovery



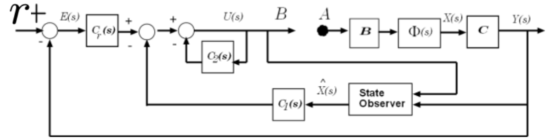
Assume that $G(s) = C\Phi(s)B$ is square and has no unstable zeros

observer: $\begin{cases} \dfrac{d}{dt}\hat{x}(t) = A\,\hat{x}(t) + B\,u(t) + L\,\tilde{y}(t) \\ \tilde{y}(t) = y(t) - C\,\hat{x}(t) \end{cases}$

observer gain $\begin{cases} L = \dfrac{1}{\mu} M_\mu C^T N^{-1} \quad N = N^T \succ 0 \quad \mu > 0 \\ AM_\mu + M_\mu A^T + BB^T - \dfrac{1}{\mu} M_\mu C^T N^{-1} C M_\mu = 0 \end{cases}$

Loop Transfer Recovery

Assume that $G(s) = C\Phi(s)B$ is square and has no unstable zeros

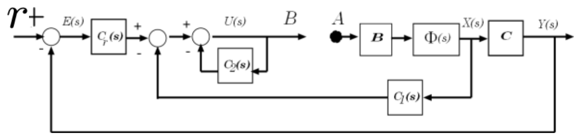


$L = \dfrac{1}{\mu} M_\mu C^T N^{-1} \quad N = N^T \succ 0 \quad \mu > 0$

$AM_\mu + M_\mu A^T + BB^T - \dfrac{1}{\mu} M_\mu C^T N^{-1} C M_\mu = 0$

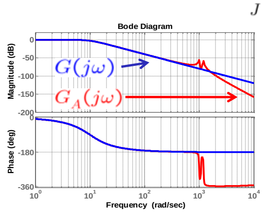
Make it approximate (point-wise in s)

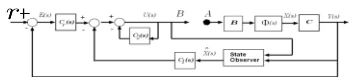
$\mu \longrightarrow 0$



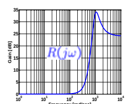
Example Hard Disk Drive

$J = \dfrac{1}{2}\int_{-\infty}^{\infty} \{Y^*(j\omega)Q_r(j\omega)Y(j\omega) + \rho\, u^*(j\omega)R(j\omega)u(j\omega)\}\, d\omega$





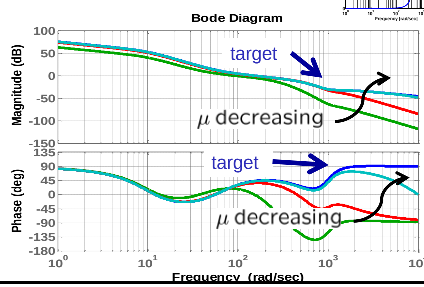
$Q_r(j\omega) = \dfrac{1}{\omega^2} \quad \rho \approx 1.6E-8$



Bode plots of

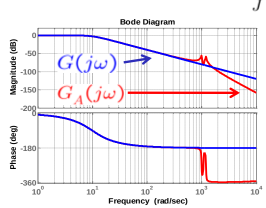
$G_o(s) = \dfrac{A(s)}{B(s)}$

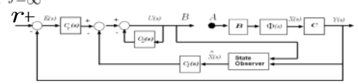
μ decreases



Example Hard Disk Drive

$J = \dfrac{1}{2}\int_{-\infty}^{\infty} \{Y^*(j\omega)Q_r(j\omega)Y(j\omega) + \rho\, u^*(j\omega)R(j\omega)u(j\omega)\}\, d\omega$





$Q_r(j\omega) = \dfrac{1}{\omega^2} \quad \rho \approx 1.6E-8$