CDS 101/110a: Lecture 8-2
Limits on Performance

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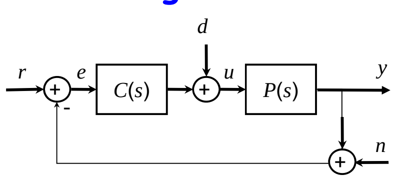
Goals:
- Describe limits of performance on feedback systems
- Introduce Bode's integral formula and the "waterbed" effect
- Show some of the limitations of feedback due to RHP poles and zeros

Reading:
- Åström and Murray, *Feedback Systems,* Ch 11

Algebraic Constraints on Performance

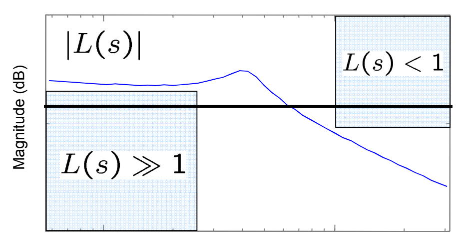


$$H_{er} = \frac{1}{1+PC} =: S$$ Sensitivity function

$$H_{yn} = \frac{PC}{1+PC} =: T$$ Complementary sensitivity function

Goal: keep S & T small
- S small ⇒ low tracking error
- T small ⇒ good noise rejection (and robustness [CDS 110b])

Problem: S + T = 1
- Can't make *both* S & T small at the same frequency
- Solution: keep S small at low frequency and T small at high frequency
- Loop gain interpretation: keep L large at low frequency, and small at high frequency



- Transition between large gain and small gain complicated by stability (phase margin)

Sensitivity

- From Rowley & Battin, *Fundamentals & Applications of Modern Flow Control*, Ch 5
- Example plotted is:

$$\frac{20}{(s+1)(s+2)(s+3)}$$

- Plot is typical; as magnitude decreases, phase increases

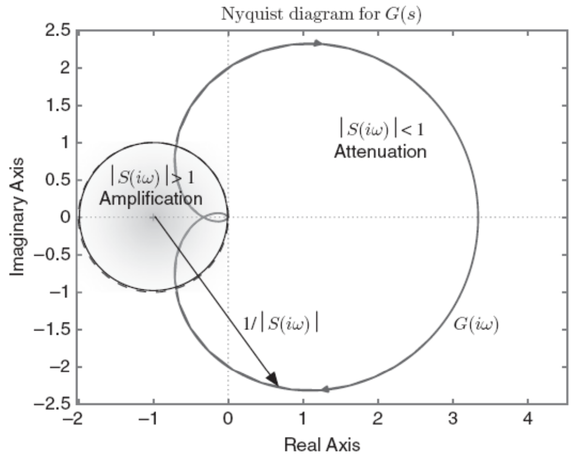


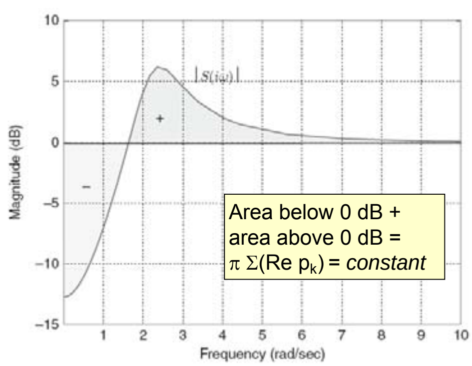
Fig. 4 Nyquist plot of the loop gain $G(s) = P(s)C(s)$ for the system (29). For frequencies for which $G(i\omega)$ enters the unit circle centered about the −1 point, disturbances are amplified and, for frequencies for which $G(s)$ lies outside this circle, disturbances are attenuated relative to open-loop.

Bode's Integral Formula and the Waterbed Effect

Bode's integral formula for S = 1/(1+PC) = 1/(1+L):

- Let p_k be the *unstable* poles of $L(s)$ and assume relative degree of $L(s) \geq 2$
- Theorem: the area under the sensitivity function is a conserved quantity:

$$\int_0^\infty \log_e |S(j\omega)| d\omega = \int_0^\infty \log_e \frac{1}{|1+L(j\omega)|} d\omega = \pi \sum \mathrm{Re}\, p_k$$

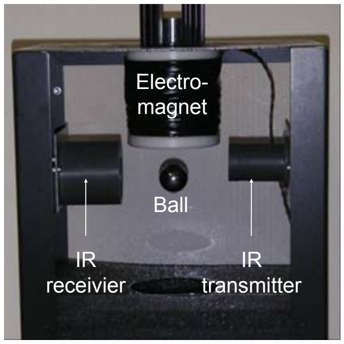


Waterbed effect:

- Making sensitivity smaller over some frequency range requires *increase* in sensitivity someplace else
- Presence of RHP poles makes this effect worse
- Actuator bandwidth further limits what you can do
- Note: area formula is linear in ω; Bode plots are logarithmic

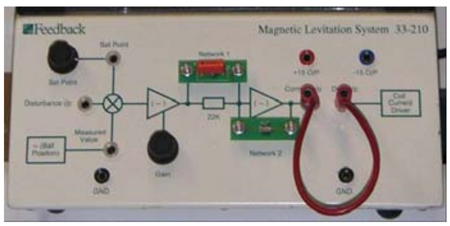
Fig. 5 Magnitude of $S(i\omega)$, illustrating the area rule (31): for this system, the area of attenuation (denoted −) must equal the area of amplification (denoted +), no matter what controller $C(s)$ is used.

Example: Magnetic Levitation



System description

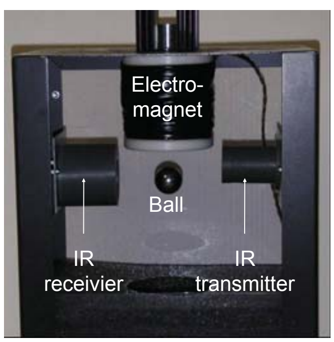
- Ball levitated by electromagnet
- Inputs: current thru electromagnet
- Outputs: position of ball (from IR sensor)
- States: $z, \dot{z}$
- Dynamics: *F* = *ma*, *F* = magnetic force generated by wire coil



Controller circuit

- Active R/C filter network
- Inputs: set point, disturbance, ball position
- States: currents and voltages
- Outputs: electromagnet current

Equations of Motion



Process: actuation, sensing, dynamics

$$m\ddot{z} = mg - k_m(k_A u)^2/z^2$$

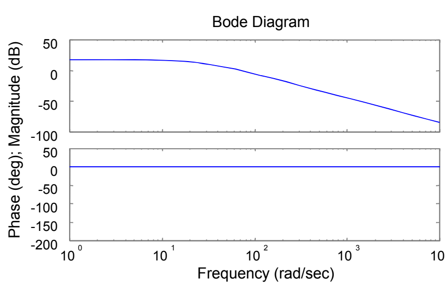
$$v_{ir} = k_T z + v_0$$

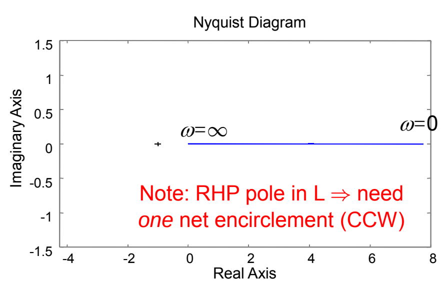
- u = current to electromagnet
- v_{ir} = voltage from IR sensor

Linearization:

$$P(s) = \frac{-k}{s^2 - r^2} \qquad k, r > 0$$

- Poles at $s = \pm r \Rightarrow$ open loop unstable



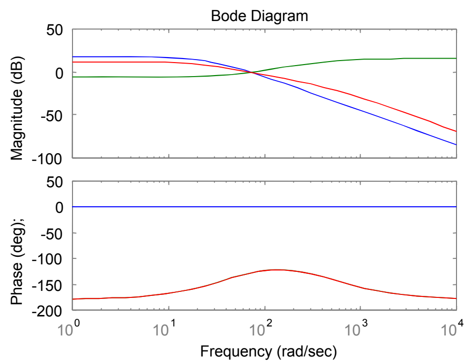


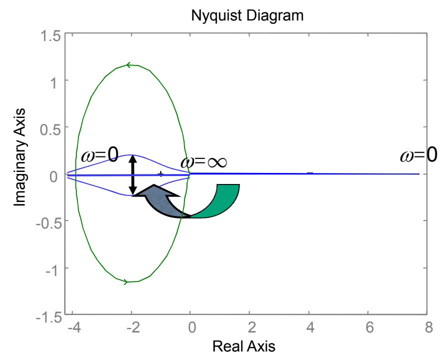
Control Design

Need to *create* encirclement
- Loop shaping is not useful here
- Flip gain to bring Nyquist plot over -1 point
- Insert phase to create CCW encirclement

Can accomplish using a lead compensator
- •Produce phase lead at crossover
- •Generates loop in Nyquist plot

$$C(s) = -k\frac{s+a}{s+b}$$





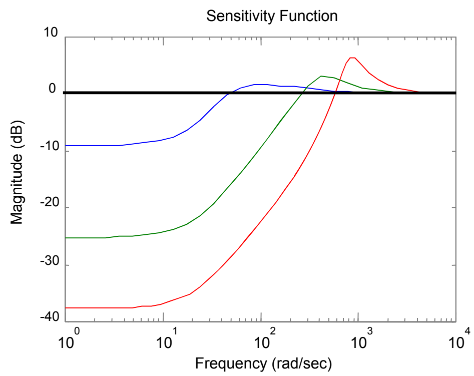
Performance Limits

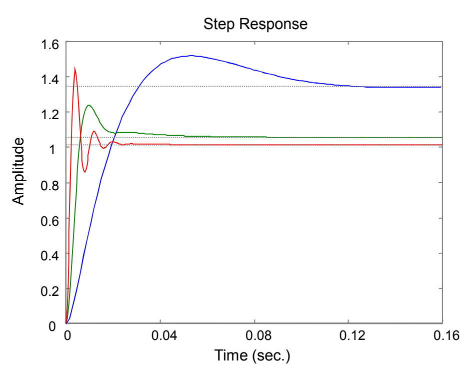
Nominal design gives low perf
- Not enough gain at low frequency
- Try to adjust overall gain to improve low frequency response
- Works well at moderate gain, but notice waterbed effect

Bode integral limits improvement

$$\int_0^\infty \log|S(j\omega)|d\omega = \pi r$$

- •Must increase sensitivity at some point



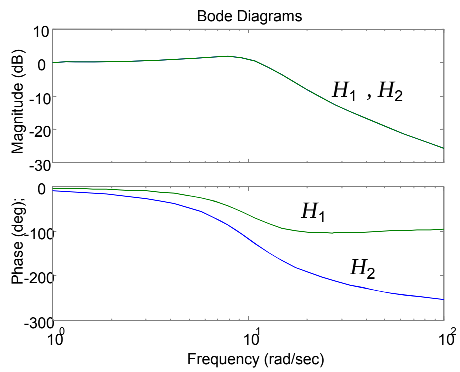


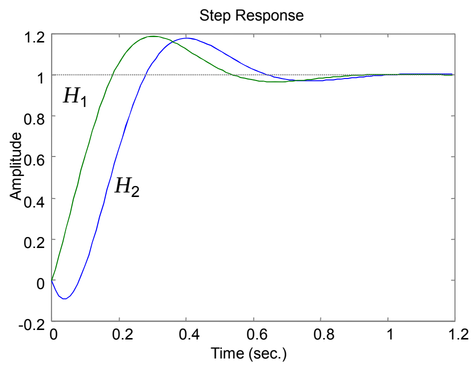
Right Half Plane Zeros

Right half plane zeros produce "non-minimum phase" behaviour

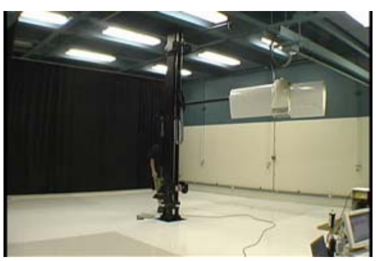
- Phase of frequency response has additional phase lag for given magnitude
- Can cause output to move *opposite* from input for a short period of time

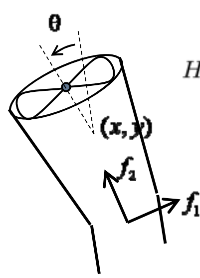
Example: $H_1 = \dfrac{s+a}{s^2 + 2\zeta\omega_n s + \omega_n^2}$ **vs** $H_2 = \dfrac{s-a}{s^2 + 2\zeta\omega_n s + \omega_n^2} = H_1(s) \times \left(-\dfrac{s-a}{s+a}\right)$





Example: Lateral Control of the Ducted Fan



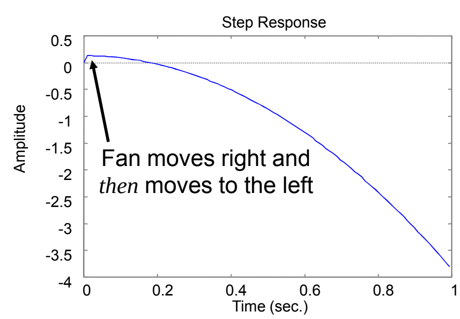


$$H_{xf_1} = \frac{s^2 - mg\ell}{Js^2 + ds - mg\ell}$$

- Poles: 0, 0, $-\sigma \pm j\omega$
- Zeros: $\pm\sqrt{mg\ell}$

Source of non-minimum phase behavior

- To move left, need to make $\theta > 0$
- To generate positive θ, need $f_1 > 0$
- Positive f_1 causes fan to move *right* initially
- Fan starts to move left after short time (as fan rotates)



Stability in the Presence of Zeros

Loop gain limitations

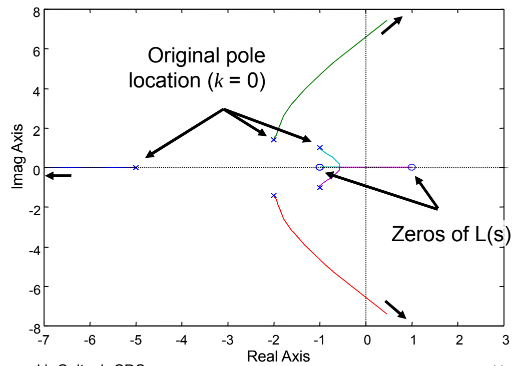
- Poles of closed loop = poles of 1 + L. Suppose $C = k\, n_c/d_c$, where k is the gain of the controller

$$1 + L = 1 + k\frac{n_c n_p}{d_c d_p} = 1 + k\frac{n}{d} = \frac{d + kn}{d}$$

- For large k, closed loop poles approach open loop zeros
- RHP zeros limit maximum gain ⇒ serious design constraint!

Root locus interpretation

- Plot location of eigenvalues as a function of the loop gain k
- Can show that closed loop poles go from open loop poles (k = 0) to open loop zeros (k = ∞)



Summary: Limits of Performance

Many limits to performance

- Algebraic: S + T = 1
- RHP poles: Bode integral formula
- RHP zeros: Waterbed effect on peak of S

Main message: try to avoid RHP poles and zeros whenever possible (eg, re-design)

$$\int_0^\infty \log_e |S(j\omega)| d\omega = \int_0^\infty \log_e \frac{1}{|1 + L(j\omega)|} d\omega = \pi \sum \text{Re } p_k$$