CDS 101/110a: Lecture 8-1
Frequency Domain Design

Douglas MacMynowski
15 November 2010

Goals:

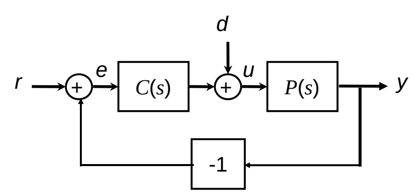
- Describe canonical control design problem and standard performance measures
- Show how to use “loop shaping” to achieve a performance specification
- Work through a detailed example of a control design problem

Reading:

- Åström and Murray, *Feedback Systems,* Ch 11
- *Advanced*: Lewis, Chapter 12

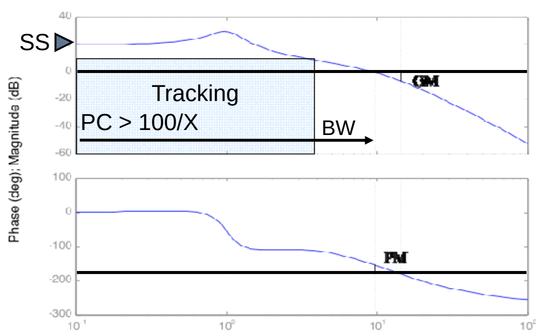
Frequency Domain Performance Specifications

Specify bounds on the loop transfer function to guarantee desired performance



$$L(s) = P(s)C(s)$$

$$H_{er} = \frac{1}{1+L} \qquad H_{yr} = \frac{L}{1+L}$$

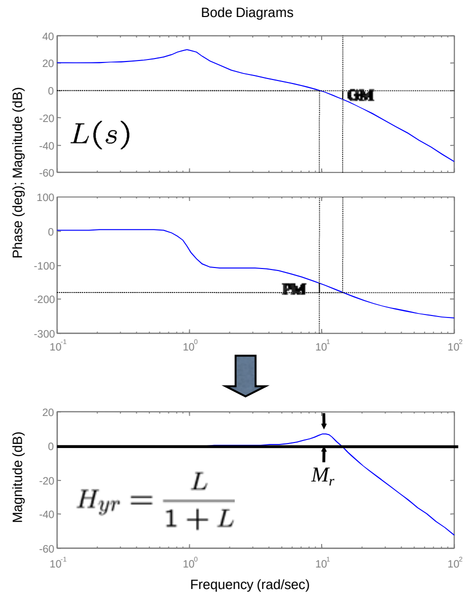


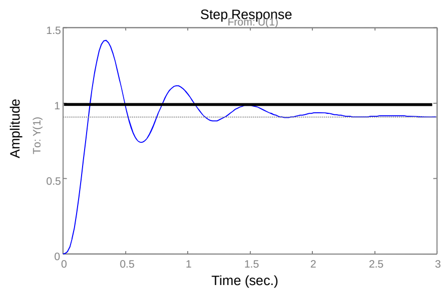
- Steady state error:
  $H_{er}(0) = 1/(1+L(0)) \simeq 1/L(0)$
  ⇒ zero frequency (“DC”) gain
- Bandwidth: assuming ~90˚ phase margin
  $$\frac{L}{1+L}(i\omega_c) = \left|\frac{1}{1+i}\right| = \frac{1}{\sqrt{2}}$$
  ⇒ sets crossover freq
- Tracking: *X*% error up to frequency ω_t ⇒ determines gain bound (1 + *PC* > 100/*X*)

Relative Stability

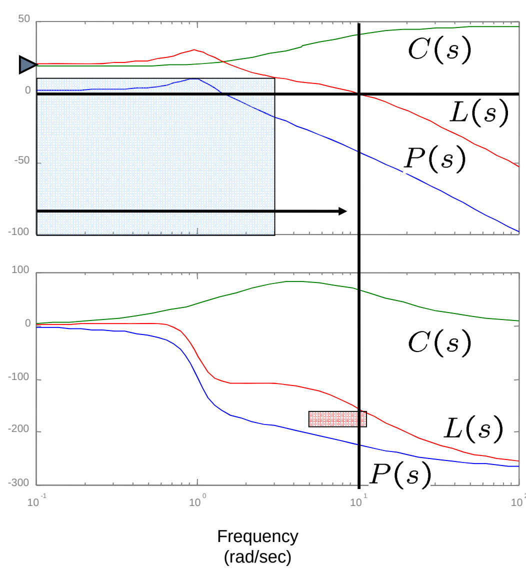
Relative stability: how stable is system to disturbances at certain frequencies?

- System can be stable but still have bad response at certain frequencies
- Typically occurs if system has low phase margin ⇒ get resonant peak in closed loop ⇒ overshoot; poor step response
- Solution: specify minimum phase margin. Typically 45˚ or more





Overview of Loop Shaping



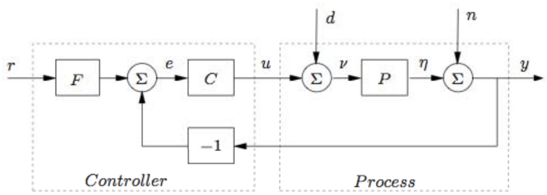
Performance specification

- ▷ Steady state error
- ☐ Tracking error
- → Bandwidth
- ☐ Relative stability

Approach: "shape" loop transfer function using *C(s)*

- $P(s)$ + specifications given
- $L(s) = P(s)\,C(s)$
  - Use $C(s)$ to choose desired shape for $L(s)$
- Important: can't set gain and phase independently

Canonical Control Design Problem



Noise and disturbances

- d = process disturbances
- n = sensor noise
- Keep track of transfer functions between all possible inputs and outputs

$$\begin{bmatrix} \eta \\ y \\ u \end{bmatrix} = \begin{bmatrix} \frac{P}{1+PC} & -\frac{PC}{1+PC} & \frac{PCF}{1+PC} \\ \frac{P}{1+PC} & \frac{1}{1+PC} & \frac{PCF}{1+PC} \\ -\frac{PC}{1+PC} & -\frac{C}{1+PC} & \frac{CF}{1+PC} \end{bmatrix} \begin{bmatrix} d \\ n \\ r \end{bmatrix}$$

Design represents a tradeoff between the quantities

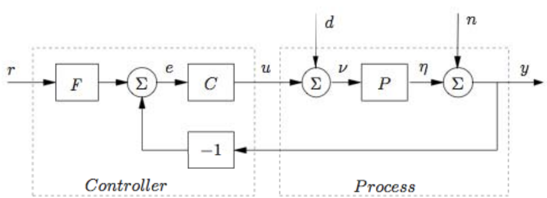
- Keep L=PC large for good performance (H_{er} << 1)
- Keep L=PC small for good noise rejection (H_{yn} << 1)

F = 1: Four unique transfer functions define performance ("Gang of Four")

- Stability is always determined by 1/(1+PC) *assuming stable process & controller*
- Numerator determined by forward path between input and output

More generally: 6 primary transfer functions; simultaneous design of each

Two Degree of Freedom Design



Transfer Functions (with F=1)

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

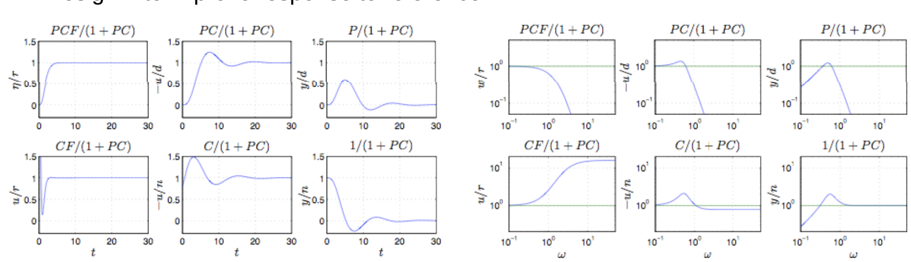
$$T = \frac{PC}{1+PC}$$ Complementary sensitivity

$$PS = \frac{P}{1+PC}$$ Load sensitivity

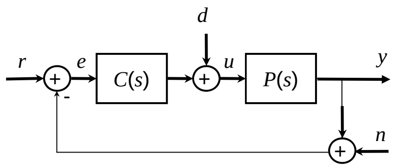
$$CS = \frac{C}{1+PC}$$ Noise sensitivity

Typical design procedure

- Design *C* to balance all requirements
- Design *F* to improve response to reference



Algebraic Constraints on Performance



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

Sensitivity function

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

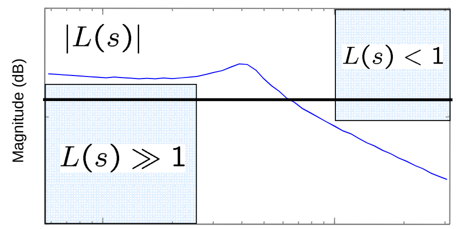
Complementary sensitivity function

Goal: keep S & T small

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

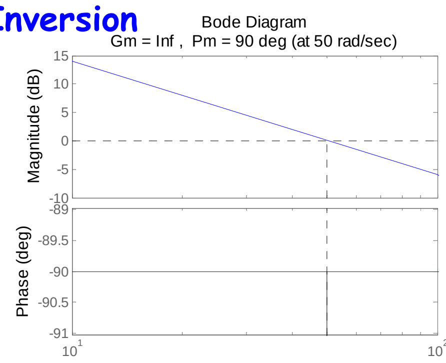
Problem: S + T = 1

- 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)

Process Inversion



Simple trick: invert out process

- Write all performance specs in terms of the desired loop transfer function
- Choose $L(s)$ that satisfies specfiications
- Choose controller by inverting $P(s)$

$$C(s) = L(s)/P(s)$$

Pros

- Very easy design process
- $L(s) = k/s$ often works very well
- Can be used as a first cut, with additional shaping to tune design

Cons

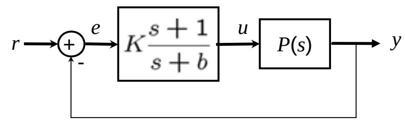
- High order controllers (at least same order as the process you are controlling)
- Requires "perfect" model of your process (since you are inverting it)
- *Does not work if you have right half plane poles or zeros* (not internal stable)

$$S = \frac{1}{1+PC} \qquad T = \frac{PC}{1+PC} \qquad PS = \frac{P}{1+PC} \qquad CS = \frac{C}{1+PC}$$

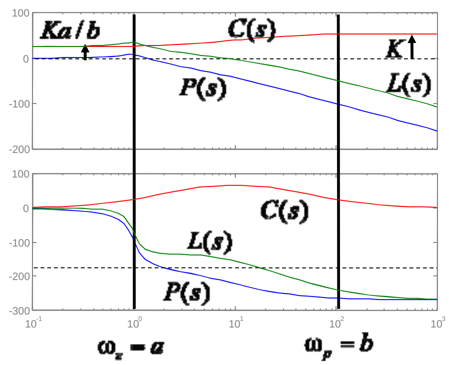
Lead compensation

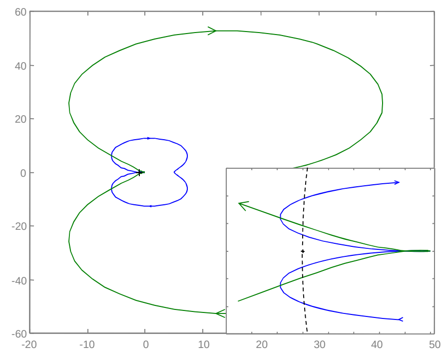
Use to increase phase in frequency band

- Effect: lifts phase by increasing gain at high frequency
- *Very* useful controller; increases PM
- Bode: add phase between zero and pole
- Nyquist: increase phase margin

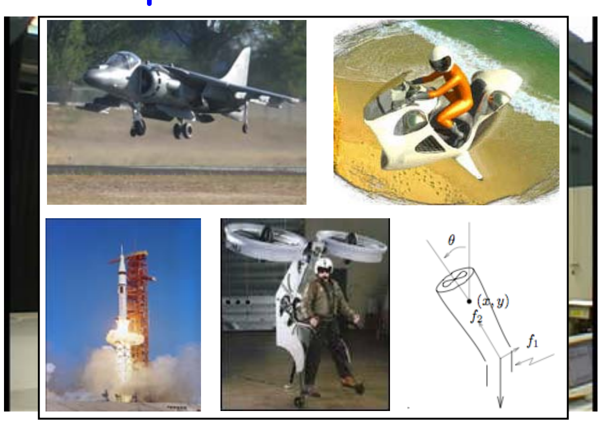


$a < b \qquad K > 0$





Example: Control of Vectored Thrust Aircraft



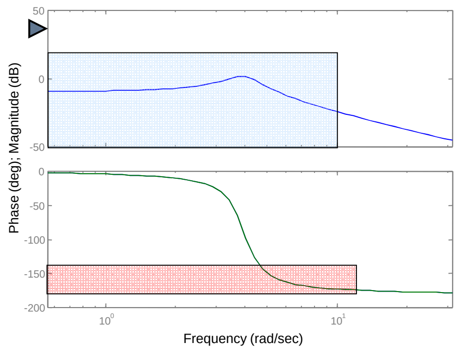
System description

- Vector thrust engine attached to wing
- Inputs: fan thrust, thrust angle (vectored)
- Outputs: position and orientation
- States: x, y, θ + derivatives
- Dynamics: flight aerodynamics

Control approach

- Design "inner loop" control law to regulate pitch (θ) using thrust vectoring
- Second "outer loop" controller regulates the position and altitude by commanding the pitch and thrust
- Basically the same approach as aircraft control laws

Performance Specification and Design Approach



Performance Specification

- $\leq$ 1% steady state error
  - Zero frequency gain > 100
- $\leq$ 10% tracking error up to 10 rad/sec
  - Gain > 10 from 0-10 rad/sec
- $\geq$ 45˚ phase margin
  - Gives good relative stability
  - Provides robustness to uncertainty

$$P(s) = \frac{r}{Js^2 + ds + mg\ell}$$

Design approach

- If choose C(s)=K, then poor phase margin
- Add phase lead in 5-50 rad/sec range
- Increase the gain to achieve steady state and tracking performance specs

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

$a = 25$

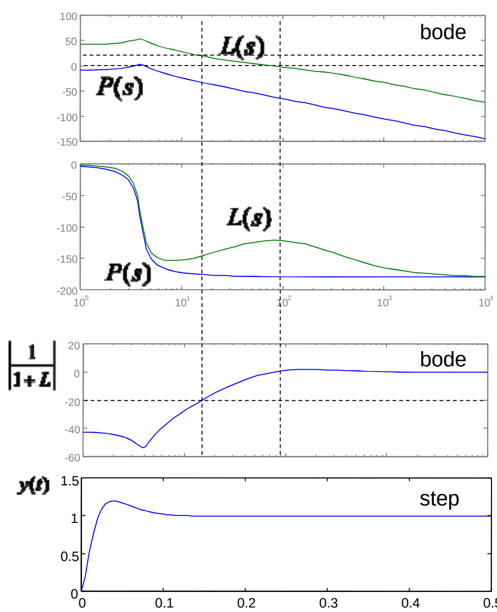
$b = 300$

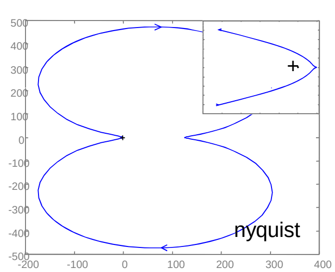
$K = 15 \times 300$

Control Design and Analysis

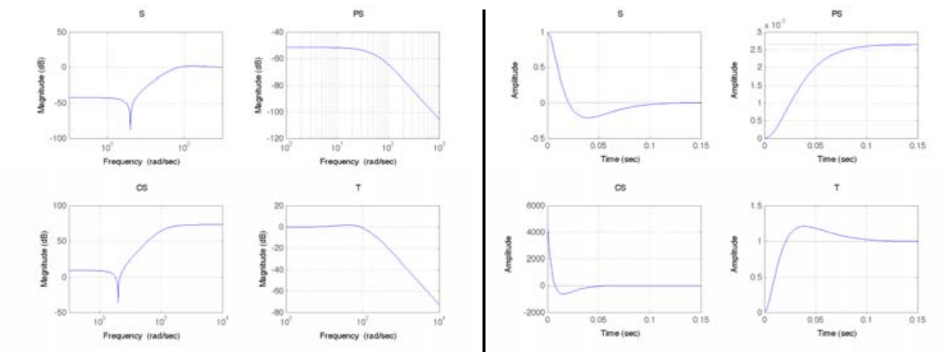
Select parameters to satisfy specs

- Place phase lead in desired crossover region (given by desired BW)
- Phase lead peaks at $\omega = \sqrt{ab}$
- Maximum phase depends on pole/zero ratio: $\phi_{\max} = 90° - 2\tan^{-1}\sqrt{a/b}$
- Set gain as needed for tracking + BW
- Verify controller using Nyquist plot, etc





Control Verification: Gang of 4



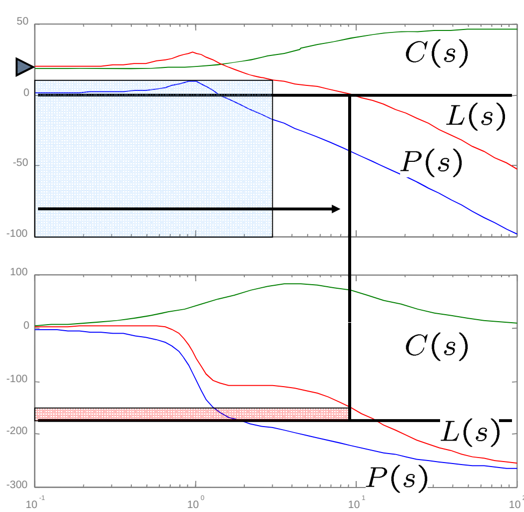
Remarks

- Check each transfer function to look for peaks, large magnitude, etc
- Example: Noise sensitivity function (*CS*) has very high gain; step response verifies poor step response
- Implication: controller amplifies noise at high frequency ⇒ will generate *lots* of motion of control actuators (flaps)
- Fix: roll off the loop transfer function faster (high frequency pole)

Summary: Loop Shaping

Loop Shaping for Stability & Performance

- Steady state error, bandwidth, tracking



Main ideas

- Performance specs give bounds on loop transfer function
- Use controller to shape response
- Gain/phase relationships constrain design approach
- Standard compensators: proportional, lead, PI