Spring 2020

控制系統
Control Systems

Unit 7A
Control System Design: Principles and Case Studies

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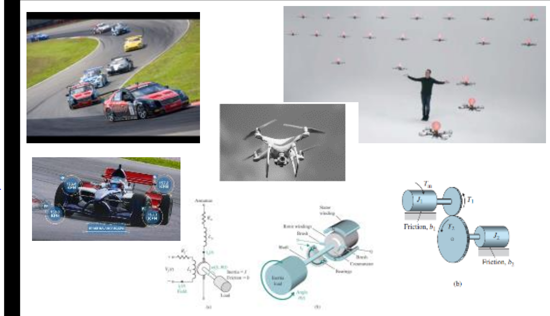
- Examples of control systems design
  - Outline of Control Systems Design
  - Satellite's Attitude Control
  - Lateral & Longitudinal Control of Boeing
  - Fuel–Air Ratio in an Automotive Engine
  - Read Write Head of a Hard Disk
  - RTP Systems in Wafer Manufacturing
  - Chemotaxis Swims Away from Trouble
  - Quadrotor Drone
- Control Tutorials Website
  - Cruise Control
  - Motor Speed
  - Motor Position
  - Suspension
  - Inverted Pendulum
  - Aircraft Pitch
  - Ball & Beam

Plant, Input, Output, Action, Goal

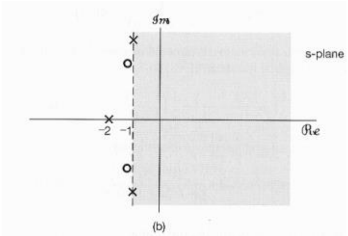
Plant (P)

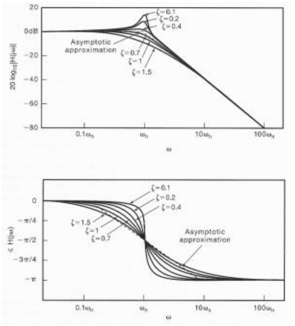


Ref (r) → ○ → **Input (u)** → Plant → **Output (y)**

$$\frac{d^2y(t)}{dt^2} + 2\,\frac{dy(t)}{dt} - 3\,y(t) = 5\,u(t)$$

$$P(s) = \frac{Y(s)}{U(s)} = \frac{5}{s^2 + 2\,s - 3}$$





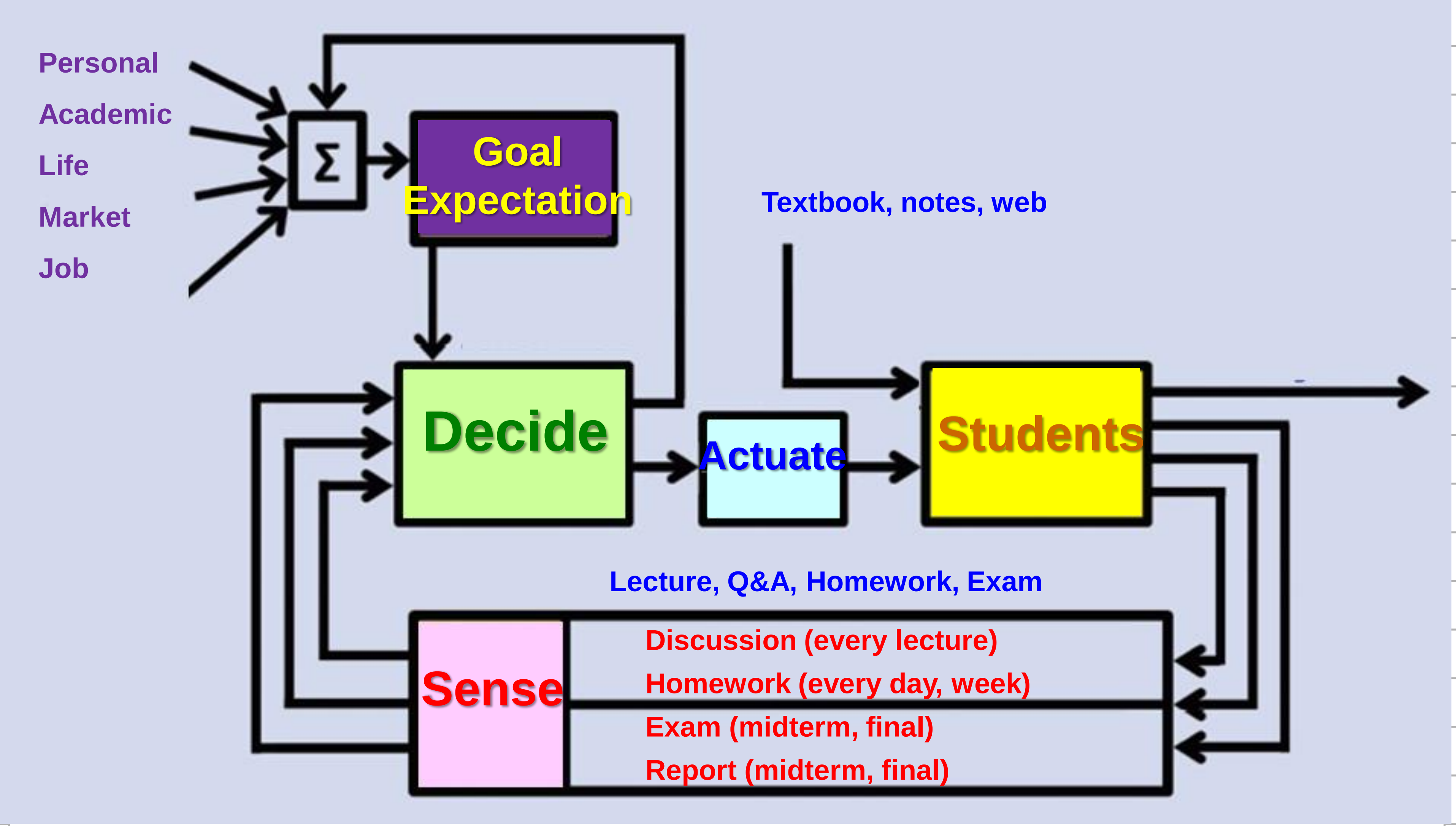
1. Model
2. Response
3. Analysis
4. Feedback
5. Control

Controller

$$\frac{d^2y(t)}{dt^2} + 4\,\frac{dy(t)}{dt} + 3\,y(t) = 3\,r(t)$$

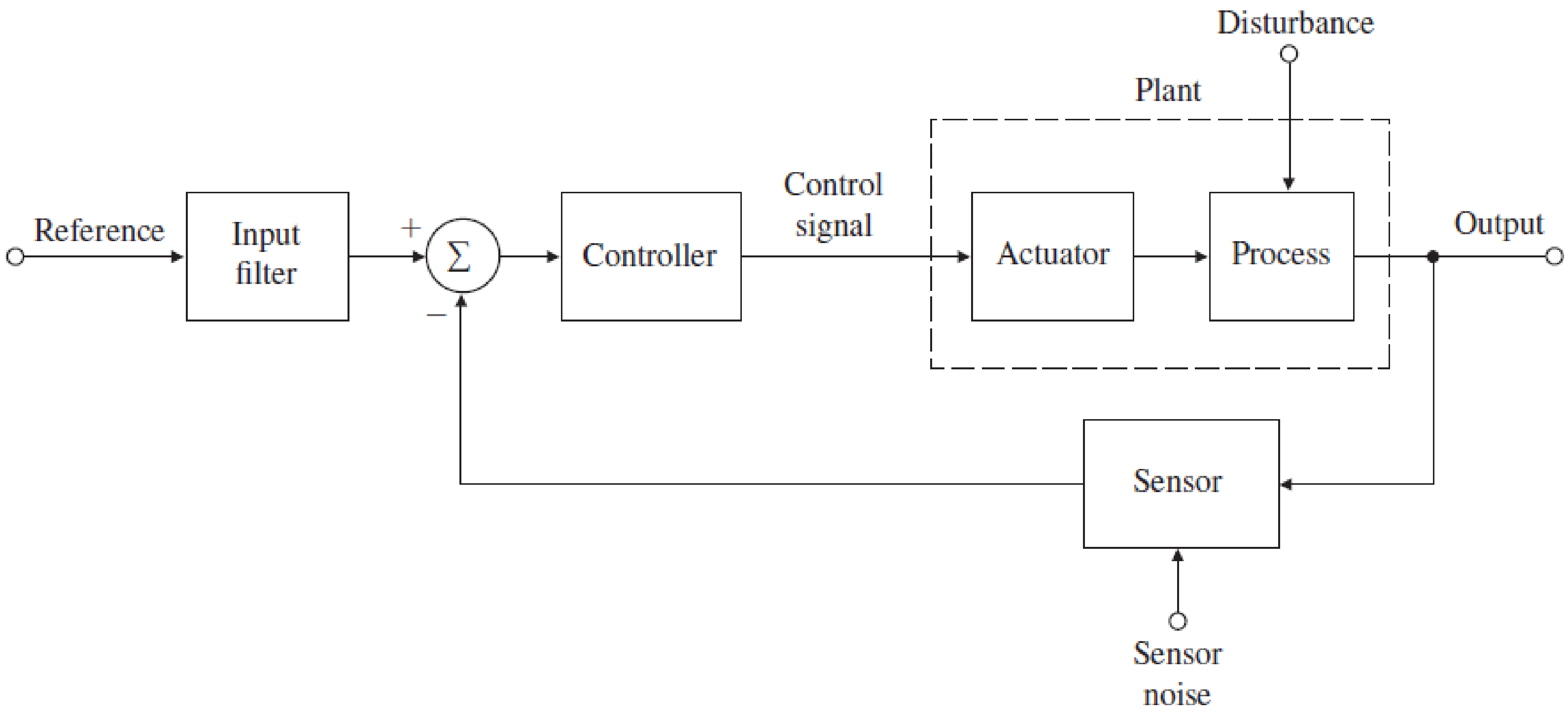
$$G(s) = \frac{Y(s)}{R(s)} = \frac{3}{s^2 + 4\,s + 3}$$

Feedback and Control in Teaching and Learning



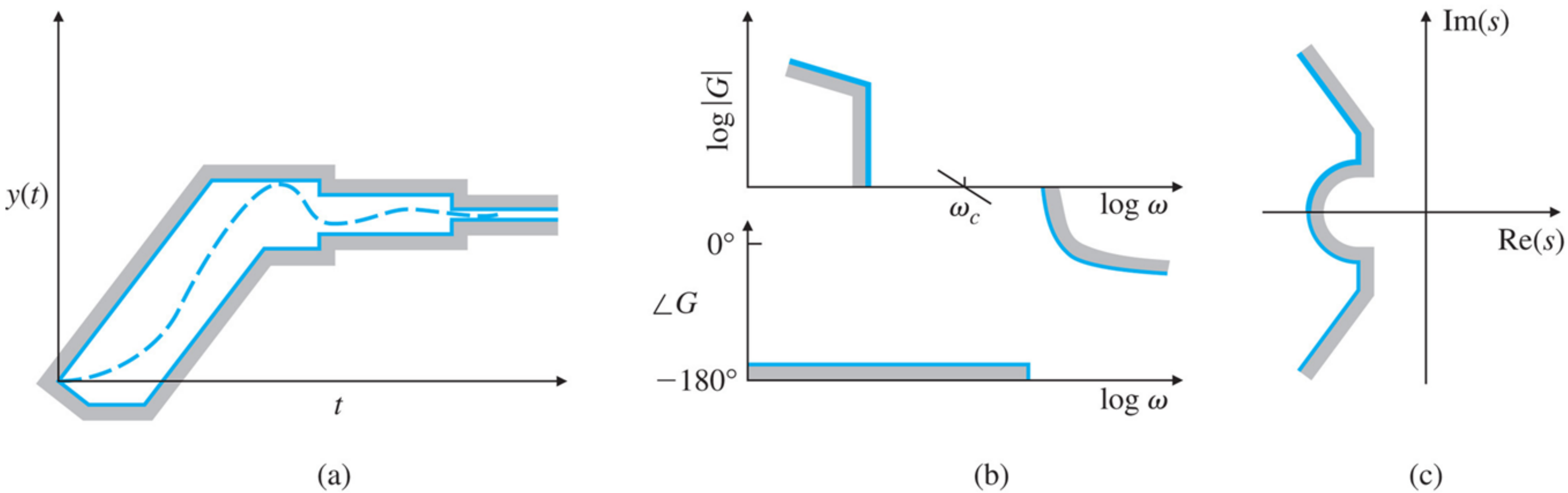
Source：IEEE CSM 2013

Key Terminologies in Feedback and Control



- (Step 1)
- Understand the process and translate dynamic performance requirements into time, frequency, or pole-zero specifications.

  – a step response inside some constraint boundaries
  – an open-loop frequency response satisfying certain constraints
  – closed-loop poles to the left of some constraint boundary



- (Step 2)
- Select sensors

  – Select the types and number of sensors considering location, technology,

Number of sensors and locations:	Select minimum required number of sensors and their optimal locations
Technology:	Electric or magnetic, mechanical, electromechanical, electro-optical, piezoelectric
Functional performance:	Linearity, bias, accuracy, bandwidth, resolution, dynamic range, noise
Physical properties:	Weight, size, strength
Quality factors:	Reliability, durability, maintainability
Cost:	Expense, availability, facilities for testing and maintenance

- (Step 3)
- Select actuators

  – The device that influences the response is the actuator

  – Select the types and number of actuators considering location, technology, noise, and power

Number of actuators and locations:	Select minimum required actuators and their optimal locations
Technology:	Electric, hydraulic, pneumatic, thermal, other
Functional performance:	Maximum force possible, extent of the linear range, maximum speed possible, power, efficiency, etc.
Physical properties:	Weight, size, strength
Quality factors:	Reliability, durability, maintainability
Cost:	Expense, availability, facilities for testing and maintenance

Outline of Control Systems Design

- (Step 4)
- Construct a linear model
  - Construct a linear model of the process, actuator, and sensor

- (Step 5)
- Try a simple proportional-integral-derivative (PID) or lead-lag design
  - Try a simple trial design based on the concepts of lead-lag compensation or PID control

- (Step 6)
- Evaluate/verify plant
  - Consider modifying the plant itself for improved closed-loop control

- (STEP 7)
- Try an optimal design (State space design)

  – If the performance from the simple compensator in Step 5 is not adequate, perform a trial pole-placement design based on optimal control or other criteria

  – (not included)

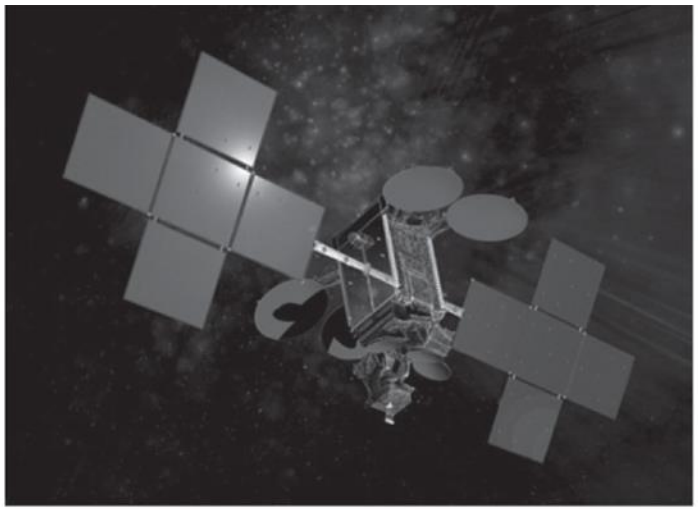
- (STEP 8)
- Build a computer model, and compute (simulate) the performance of the design

  – Simulate the design, including the effects of nonlinearities, noise, and parameter variations. If the performance is not satisfactory, return to Step 1 and repeat. Consider modifying the plant itself for improved closed-loop control

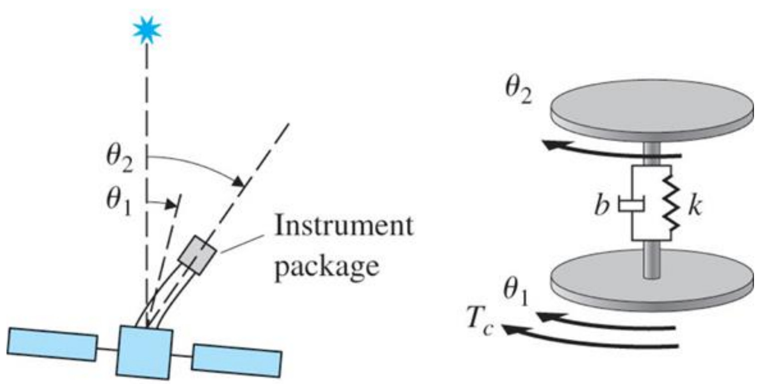
- (STEP 9)
- Build a prototype

Example 10.1 Satellite's Attitude Control

- (STEP 1.) Understand the process and its performance specifications
  - the vehicle has an astronomical survey mission requiring accurate pointing of a scientific sensor package.



(a)



(b)

θ_1 : the angle of the main satellite with respect to the star

θ_2 : satellite attitude

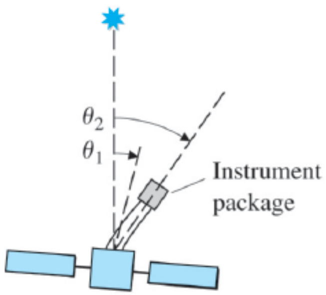
SPEC:
– a transient settling time of 20 sec
– an overshoot of no more than 15 %

Example 10.1 Satellite's Attitude Control

- (STEP 2.) Select sensors
  - Star tracker to obtain θ_2
  - Rate gyto to have $\dot{\theta}_2$

SPEC:
– a transient settling time of 20 sec
– an overshoot of no more than 15 %

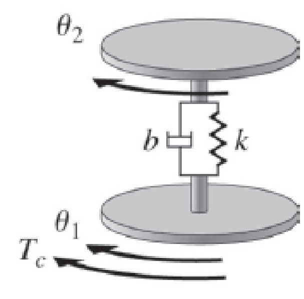
- (STEP 3.) Select actuators
  - Cold-gas jets as being fast and adequately accurate



- (STEP 4.) Make a linear model

$$J_1\ddot{\theta}_1 + b(\dot{\theta}_1 - \dot{\theta}_2) + k(\theta_1 - \theta_2) = T_c$$

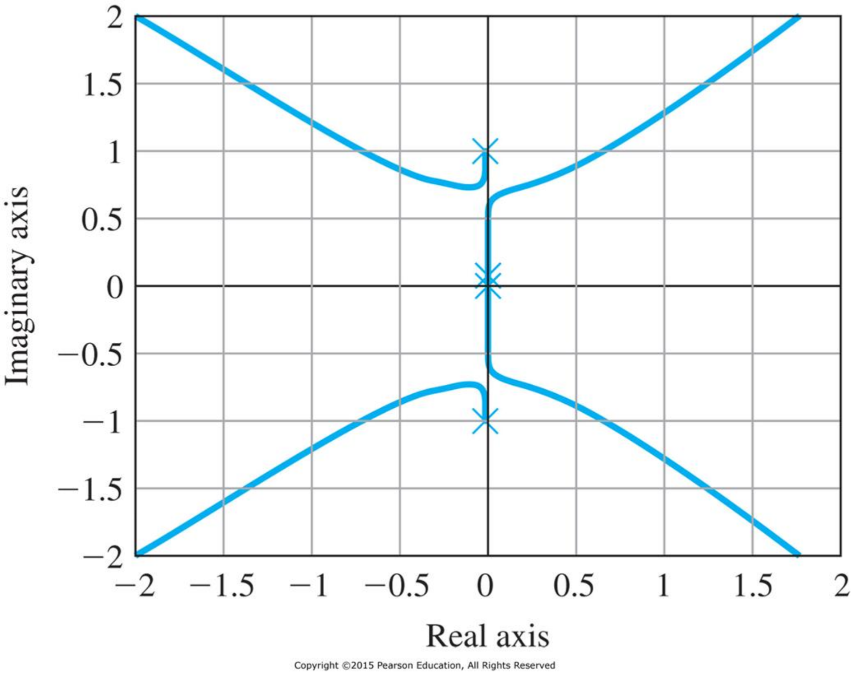
$$J_2\ddot{\theta}_1 + b(\dot{\theta}_2 - \dot{\theta}_1) + k(\theta_2 - \theta_1) = 0$$



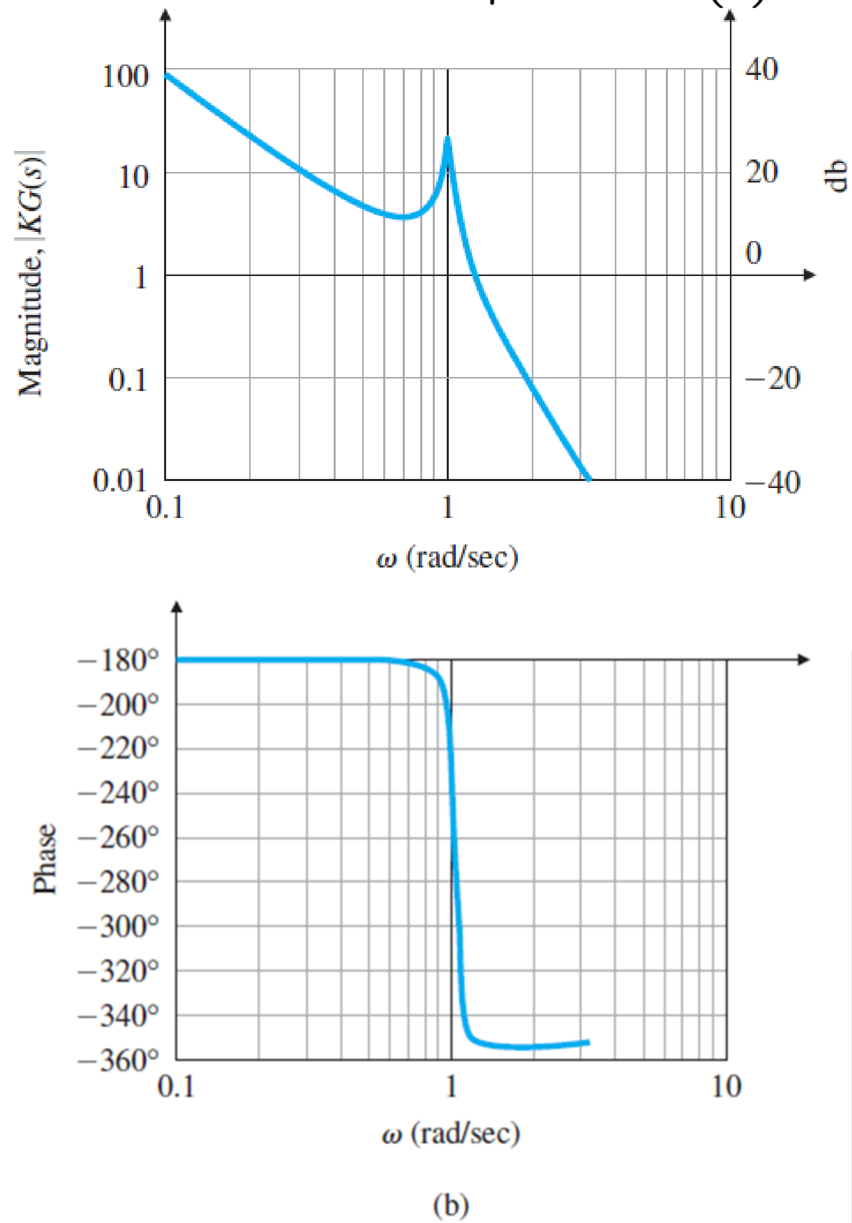
$$G(s) = \frac{\Theta_2(s)}{T_c(s)} = \frac{10bs + 10k}{s^2(s^2 + 11bs + 11k)} \qquad (J_1 = 1, J_2 = 0.1)$$

- (STEP 5.) Try a lead-lag or P/D controller

proportional gain root locus

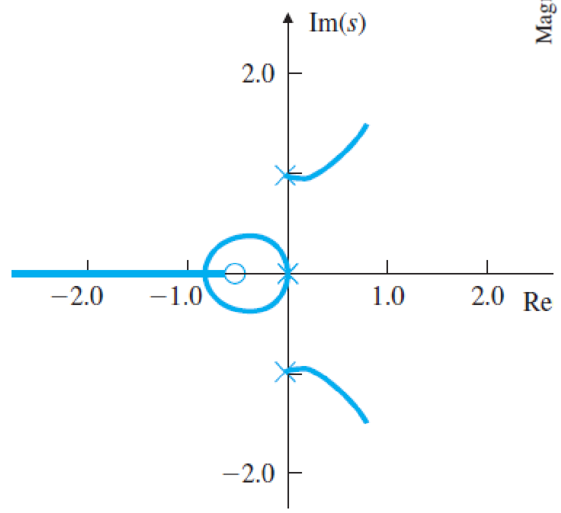


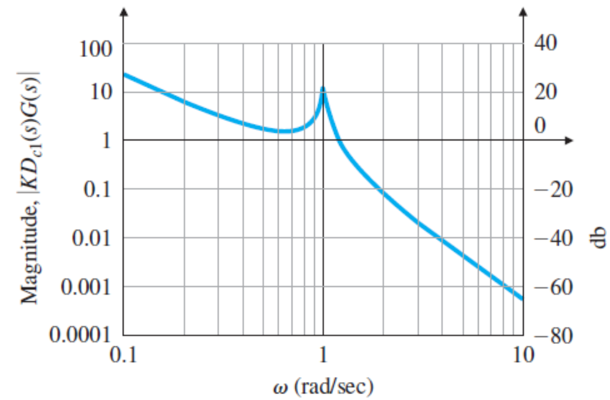
Bode plot of $G(s)$



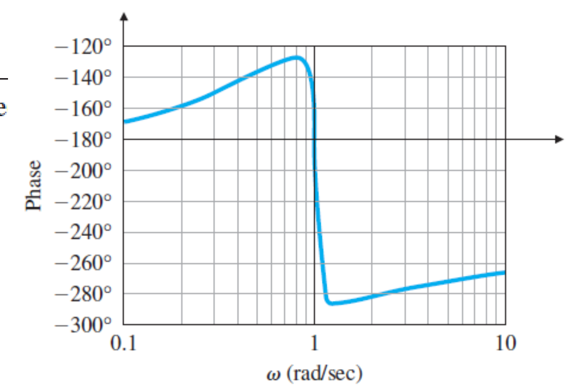
(STEP 5.) Try a lead-lag or P/D controller

- First ignore the resonance and generate a design that would be acceptable for the rigid body alone
- Take the process transfer function to be $1/s^2$
- Consider the PD control, $D_c(s) = K(sT_D + 1)$
- The response objective is $\omega_n = 0.5 (rad/sec)$, $\zeta = 0.5$
- For $D_{c1}(s) = 0.25(2s + 1)$
- Unstable



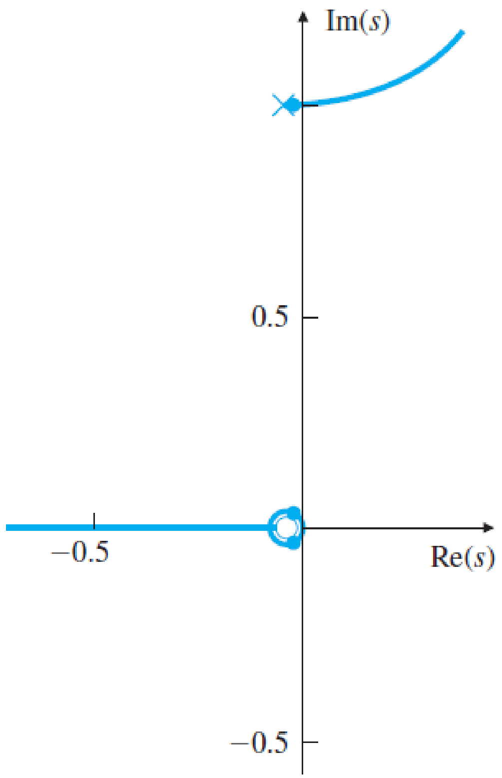


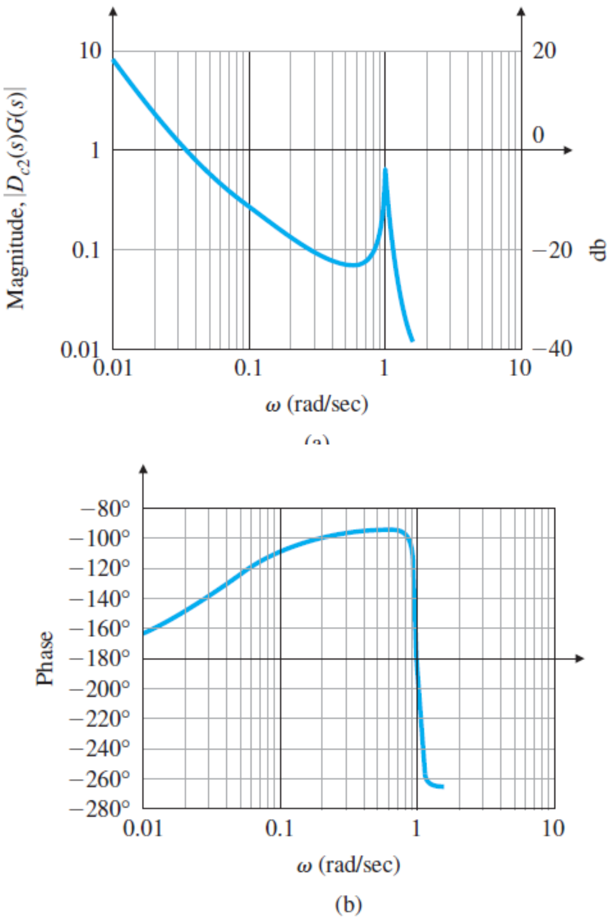
(a)



(b)

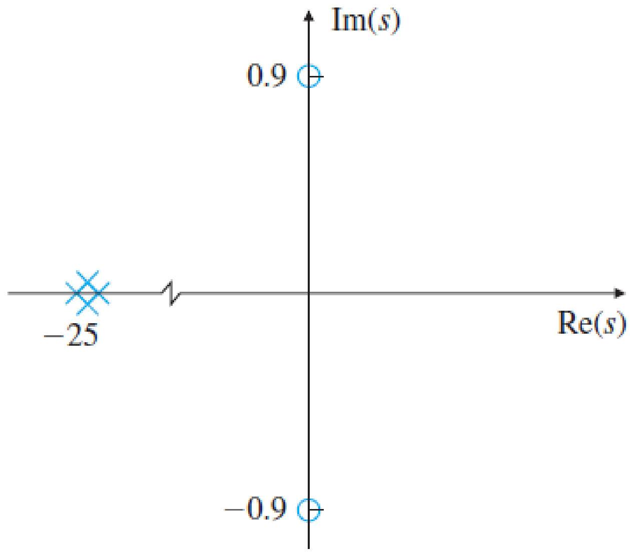
- (STEP 5.) Try a lead-lag or P/D controller
  - Lower the gain for $D_{c2}(s) = 0.001(30s + 1)$

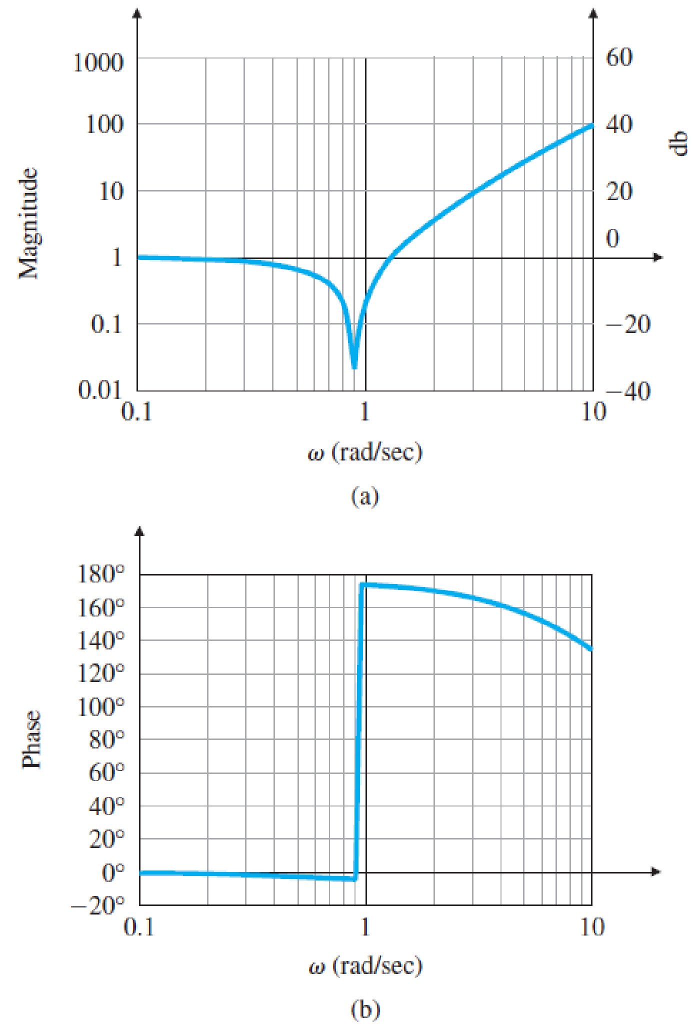




- (STEP 5.) Try a lead-lag or P/D controller
  - Consider a notch filter

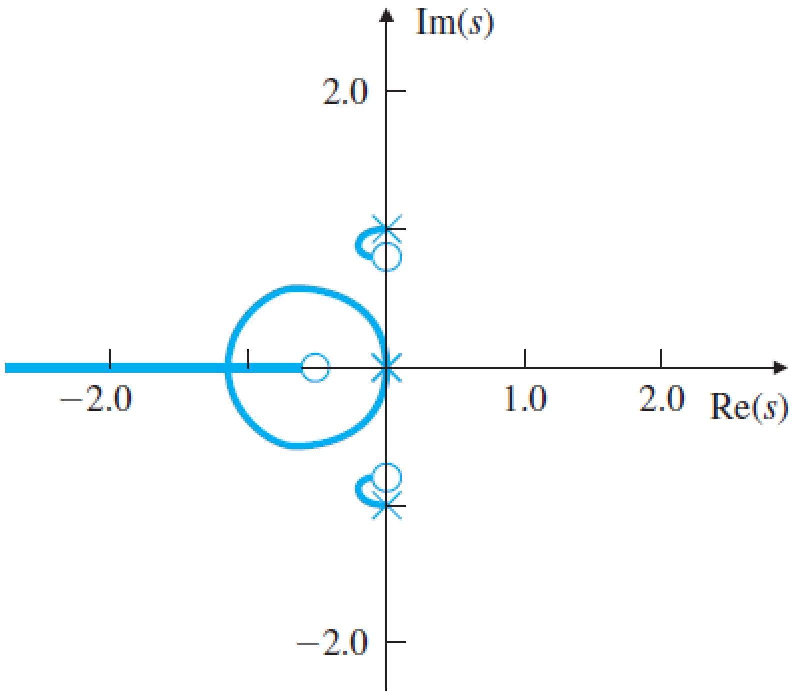
$$D_{c3}(s) = 0.25(2s+1)\frac{(s/09)^2+1}{[(s/25)+1]^2}$$

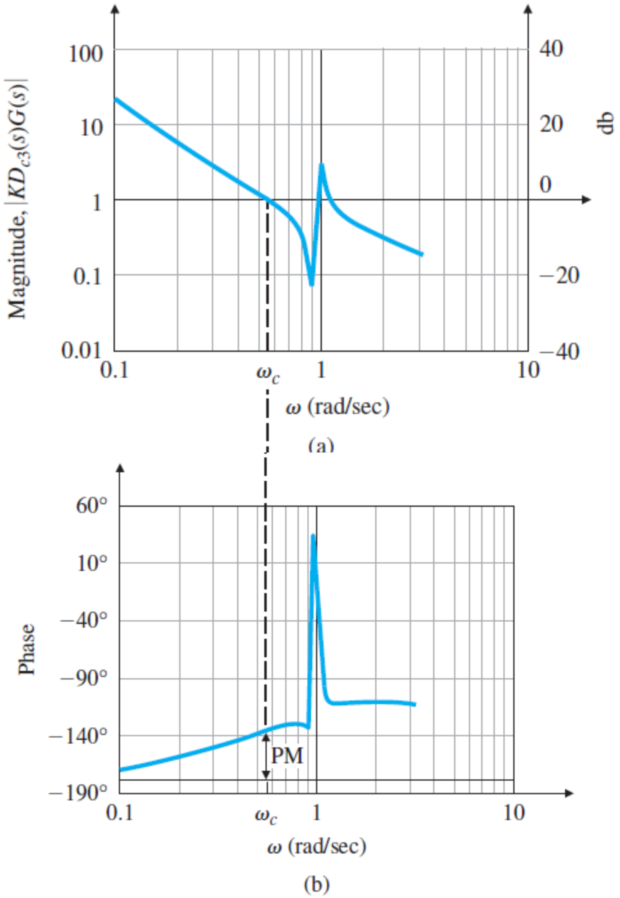




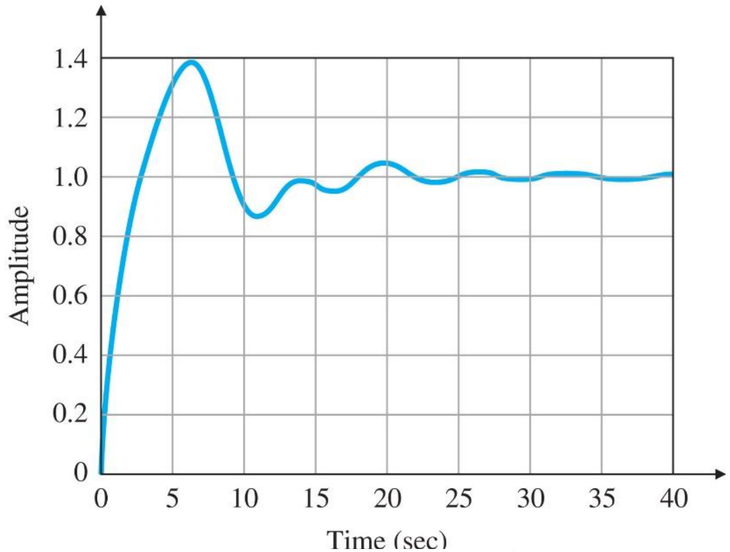
Example 10.1 Satellite's Attitude Control

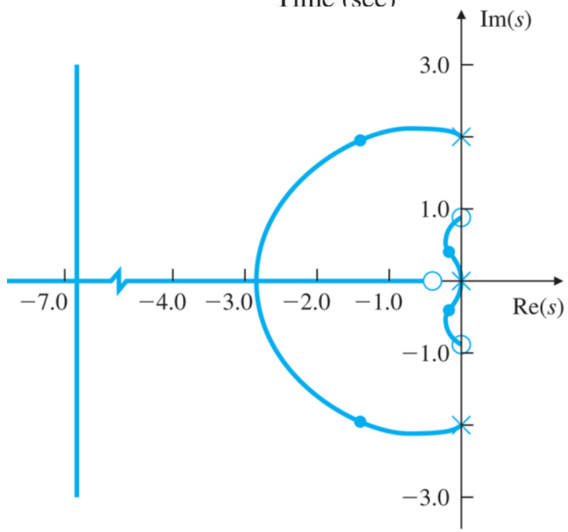
- (STEP 5.) Try a lead-lag or P/D controller
  - Response of $KD_{c3}(s)G(s)$

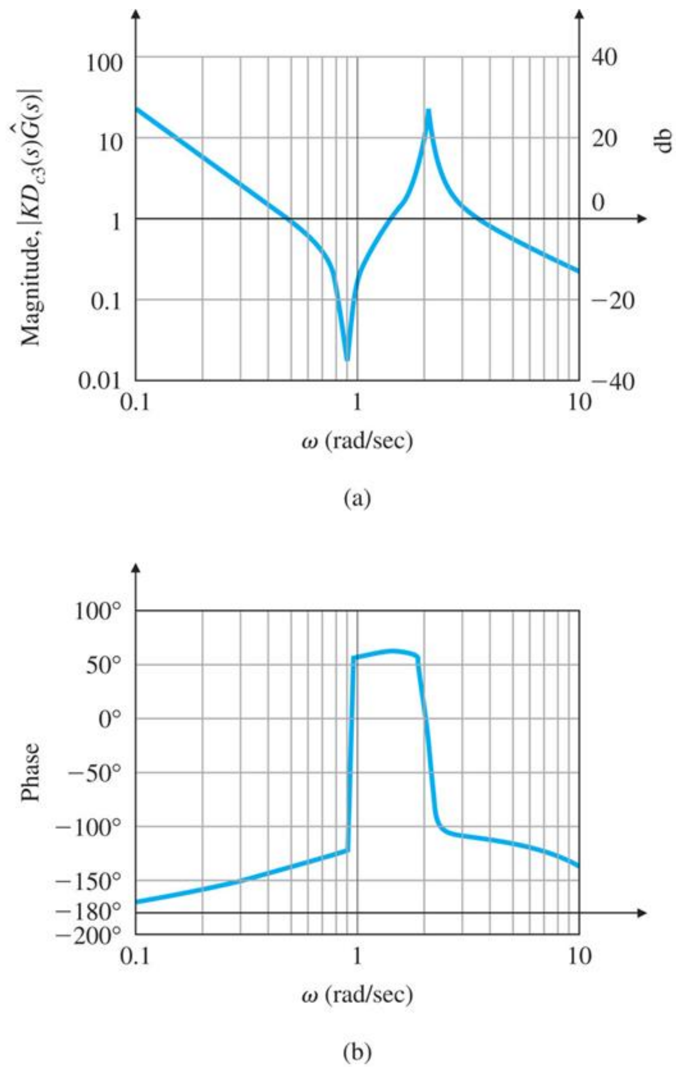




- (STEP 5.) Try a lead-lag or P/D controller
  - Closed-loop response ($\theta_2(0) = 0.2$)



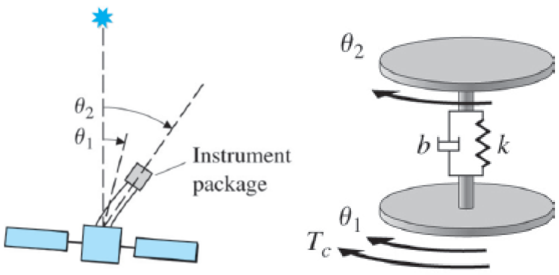




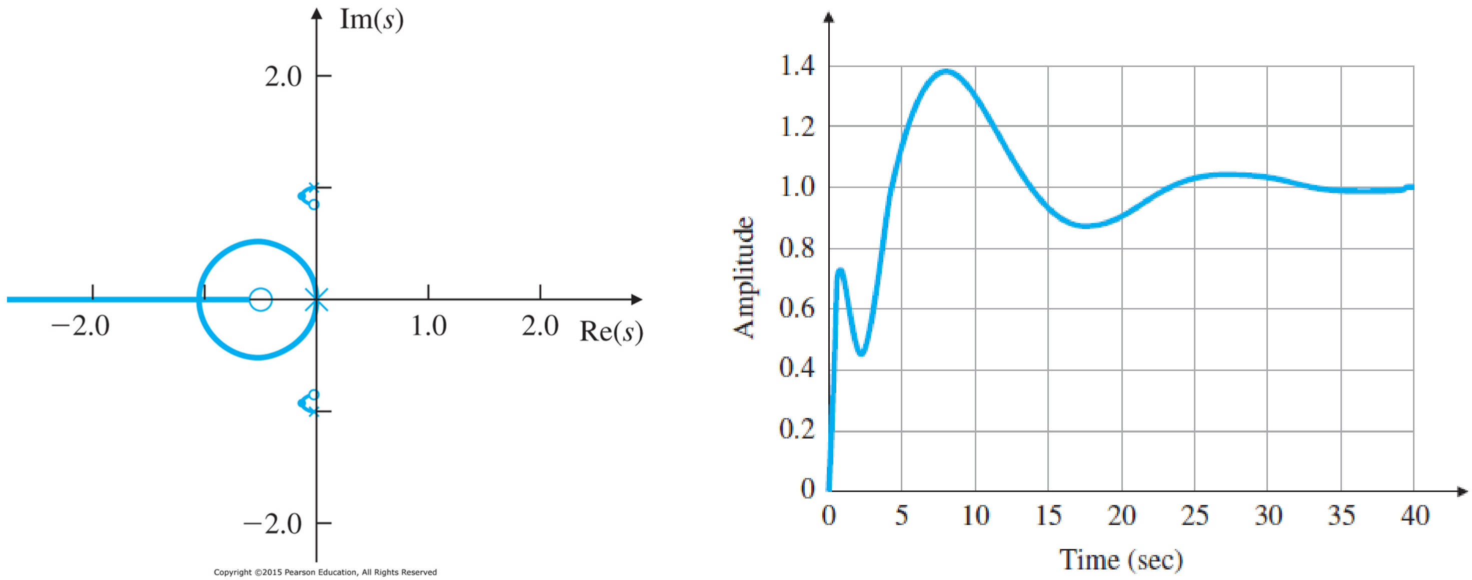
Example 10.1 Satellite's Attitude Control

- (STEP 6) Evaluate/verify the plant
  - Moving the sensor from a noncollocated position to one collocated with the actuator

$$G_0(s) = \frac{\Theta_1(s)}{T_c(s)} = \frac{(s + 0.018 \pm 0.954j)}{s^2(s + 0.02 \pm j)}$$



  - For $D_{c5}(s) = 0.25(2s+1)$, closed-loop response of $D_{c5}(s)G_0(s)$



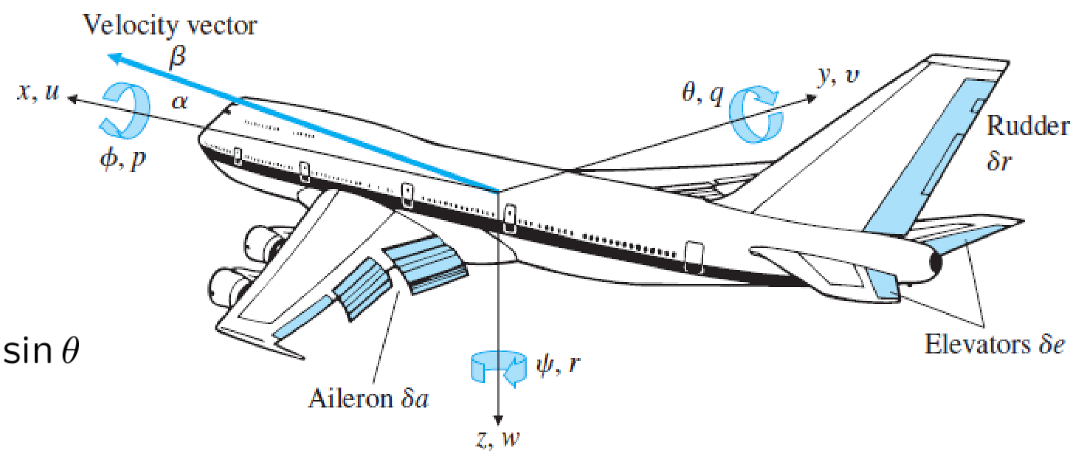
Example 10.1 Satellite's Attitude Control

- (STEP 7) Try an optimal design (State space design)

- (STEP 8) Build a computer model, and compute (simulate) the performance of the design

- (STEP 9) Build a prototype

- Equations of motion: Boeing 747



$$m(\dot{U} + qW - rV = X - mg\sin\theta + \kappa T\cos\theta$$

$$m(\dot{V} + rU - pW = Y + mg\cos\theta\sin\phi$$

$$m(\dot{W} + pV - qU = Z + mg\cos\theta\cos\phi - \kappa T\sin\theta$$

$$I_x\dot{p} + I_{xz}\dot{r} + (I_z - I_y)qr + I_{xz}qp = L$$

$$I_y\dot{q} + (I_x - I_z)pr + I_{xz}(r^2 - p^2) = M$$

$$I_z\dot{r} + +(I_y - I_x)qp - I_{xz}qr = N$$

Linearization of the system:

$\dot{U} = \dot{V} = \dot{W} = \dot{p} = \dot{q} = \dot{r} = 0$

$p_o = q_o = r_o = 0$ (reference angular velocities)

Example 10.2 Lateral and Longitudinal Control of a Boeing 747

- **Yaw damper**

- Linearized lateral motion equation

$$\begin{bmatrix} \dot\beta \\ \dot r \\ \dot p \\ \dot\phi \end{bmatrix} = \begin{bmatrix} Y_v & -U_o & V_o & g_o\cos\theta_o \\ N_v & N_r & N_p & 0 \\ L_v & L_r & L_p & 0 \\ 0 & \tan\theta_o & 1 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ r \\ p \\ \phi \end{bmatrix} + \begin{bmatrix} Y_{\delta r} & Y_{\delta a} \\ N_{\delta r} & N_{\delta a} \\ L_{\delta r} & L_{\delta a} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta r \\ \delta a \end{bmatrix}$$

(Input: δr rudder, output: r yaw rate)

- (STEP 1.) Understand the process and its performance specifications
  - Modidfy the the natural dynamics so that the plane is acceptable for the pilot to fly
  - $\omega_n \leq 0.5$ and damping ratio of $\zeta \geq 0.5$ approximately

Example 10.2 Lateral and Longitudinal Control of a Boeing 747

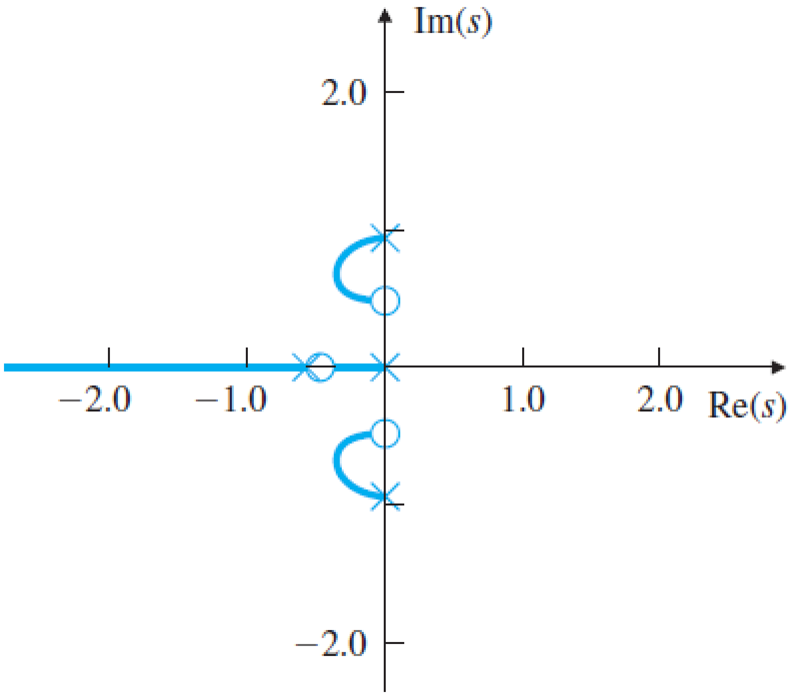
- (STEP 2) Select sensors
  - Measure the angular velocity (gyro)

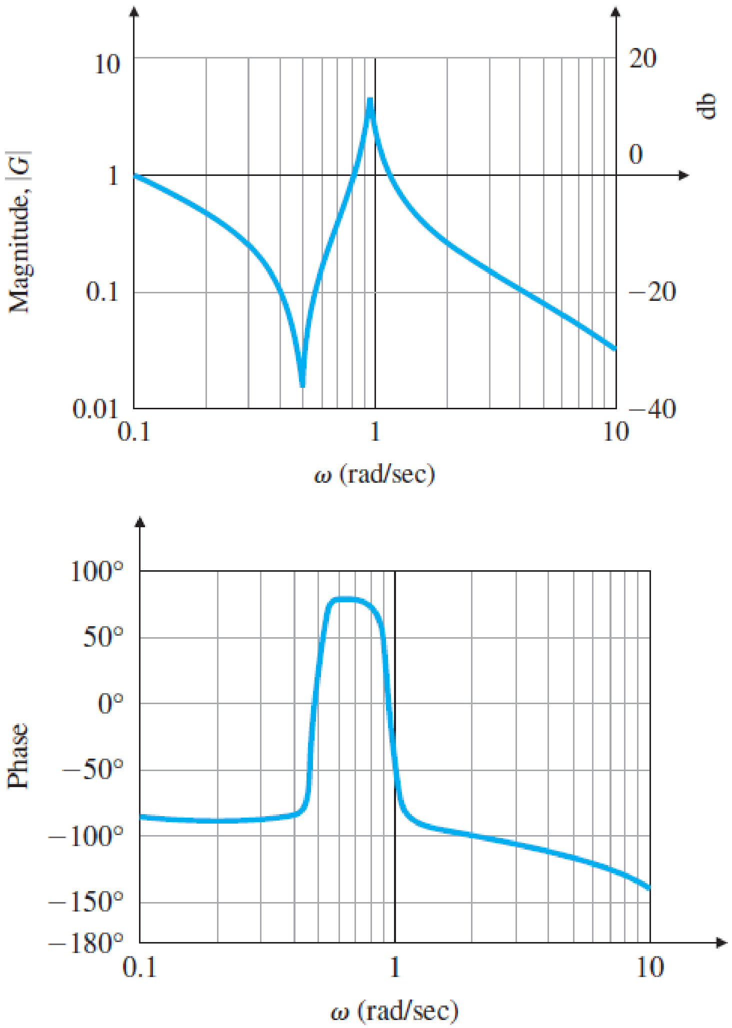
- (STEP 3) Select actuators
  - Rudder

- (STEP 4) Make a linear model

$$G(s) = \frac{r(s)}{\delta r(s)} = \frac{-0.475(s+0.498)(s+0.012 \pm 0.488j)}{(s+0.0073)(s+0.563)(s+0.033 \pm 0.947j)}$$

- (STEP 5) Try a lead-lag or PID design
  - For a proportional feedback

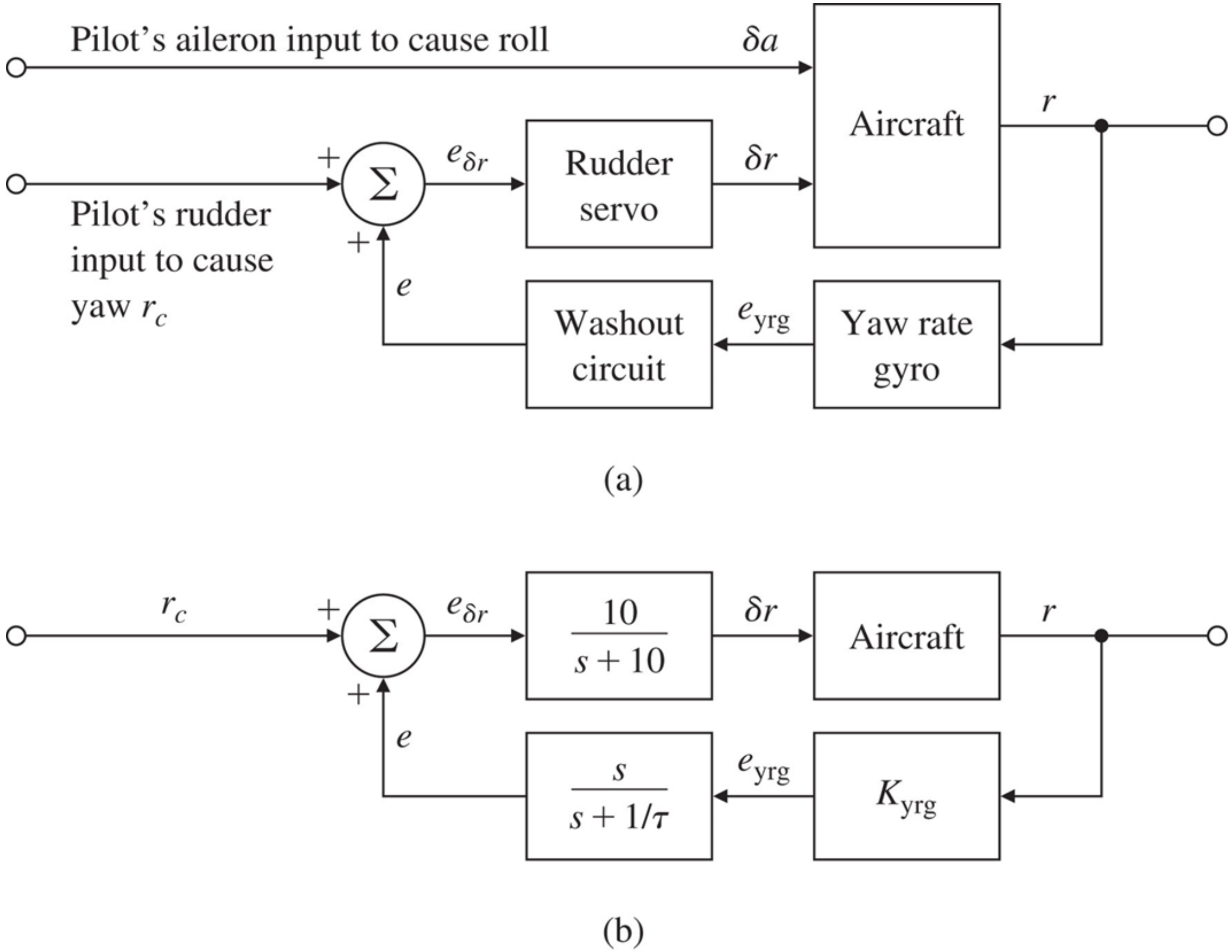




(b)

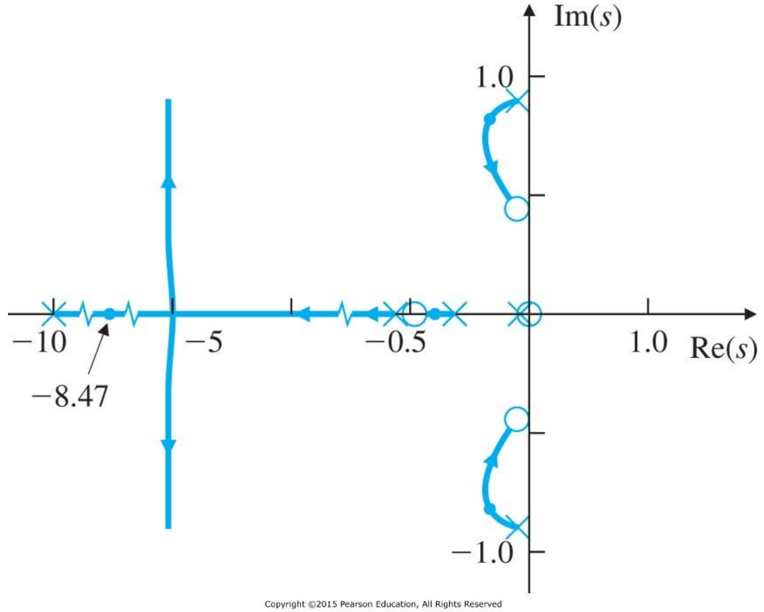
Example 10.2 Lateral and Longitudinal Control of a Boeing 747

- (STEP 5) Try a lead-lag or PID design
  - Add $H(s) = \frac{s}{1+s/\tau}$

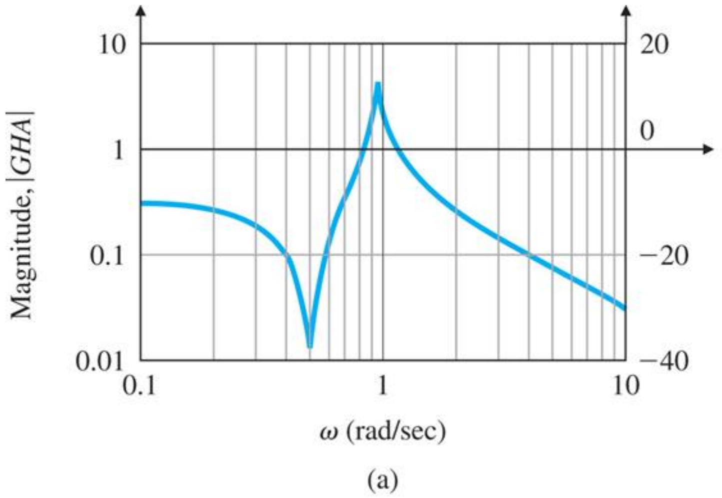


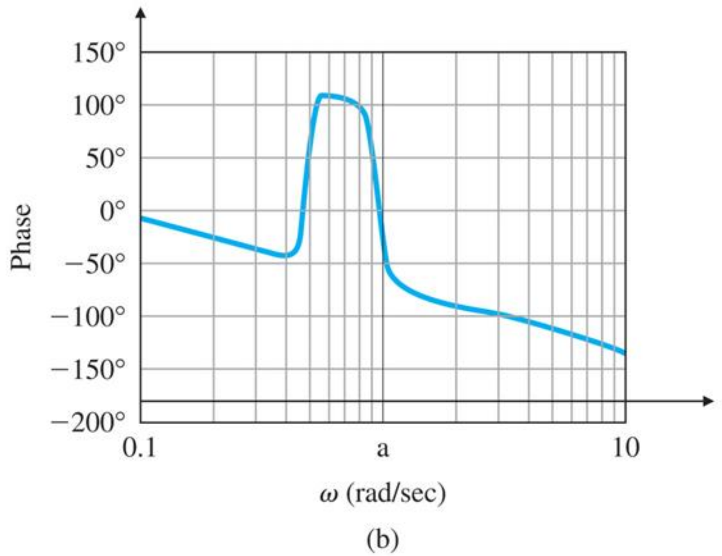
Yaw damper: (a) functional block diagram; (b) block diagram for analysis

- (STEP 5) Try a lead-lag or PID design
  - With $\tau = 3$



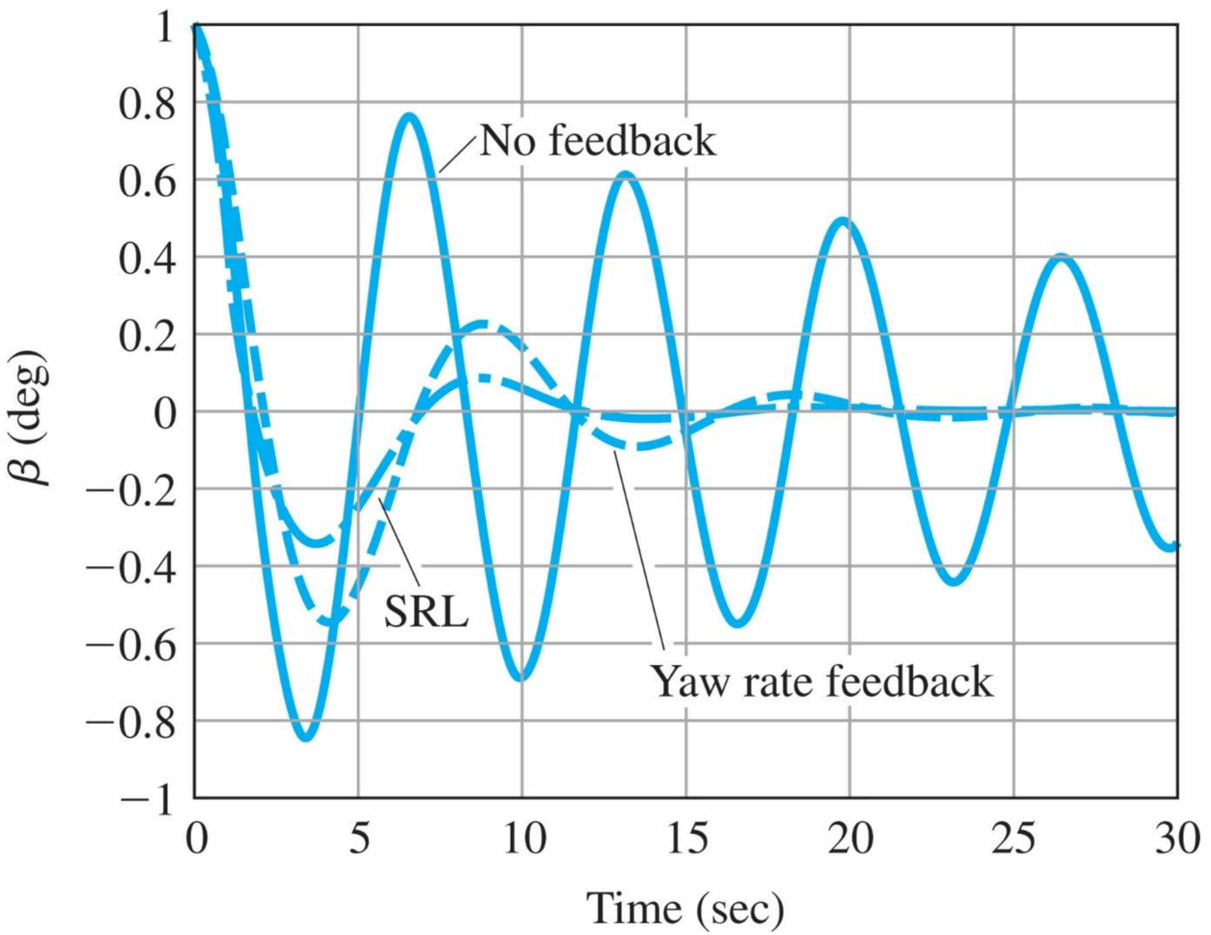
(damping ratio from 0.03 to 0.35)





Example 10.2 Lateral and Longitudinal Control of a Boeing 747

- (STEP 5) Try a lead-lag or PID design
  - With $\tau = 3$

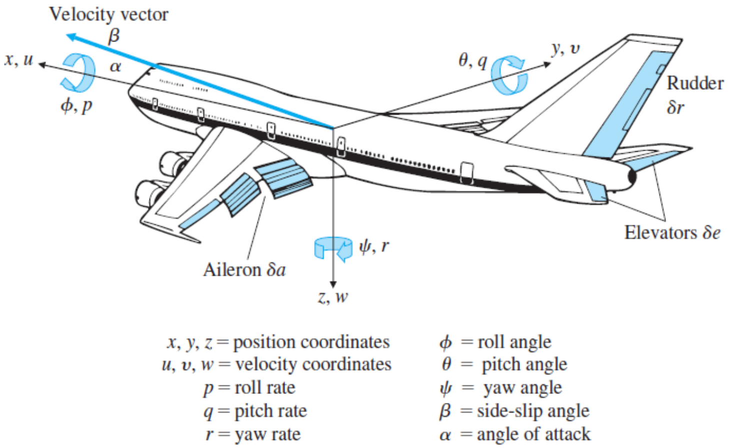


- **Altitude hold autopilot**

- (STEP 1.) Understand the process and its performance specifications
  - The design should provide the kind of ride that pilot and passenger like
  - Damping ratio $\zeta \approx 0.5$
  - The natural frequency should be "much" less than $\omega_n = 1$

- (STEP 2) Select sensors
  - Measure the altitude

- (STEP 3) Select actuators
  - Elevator δe

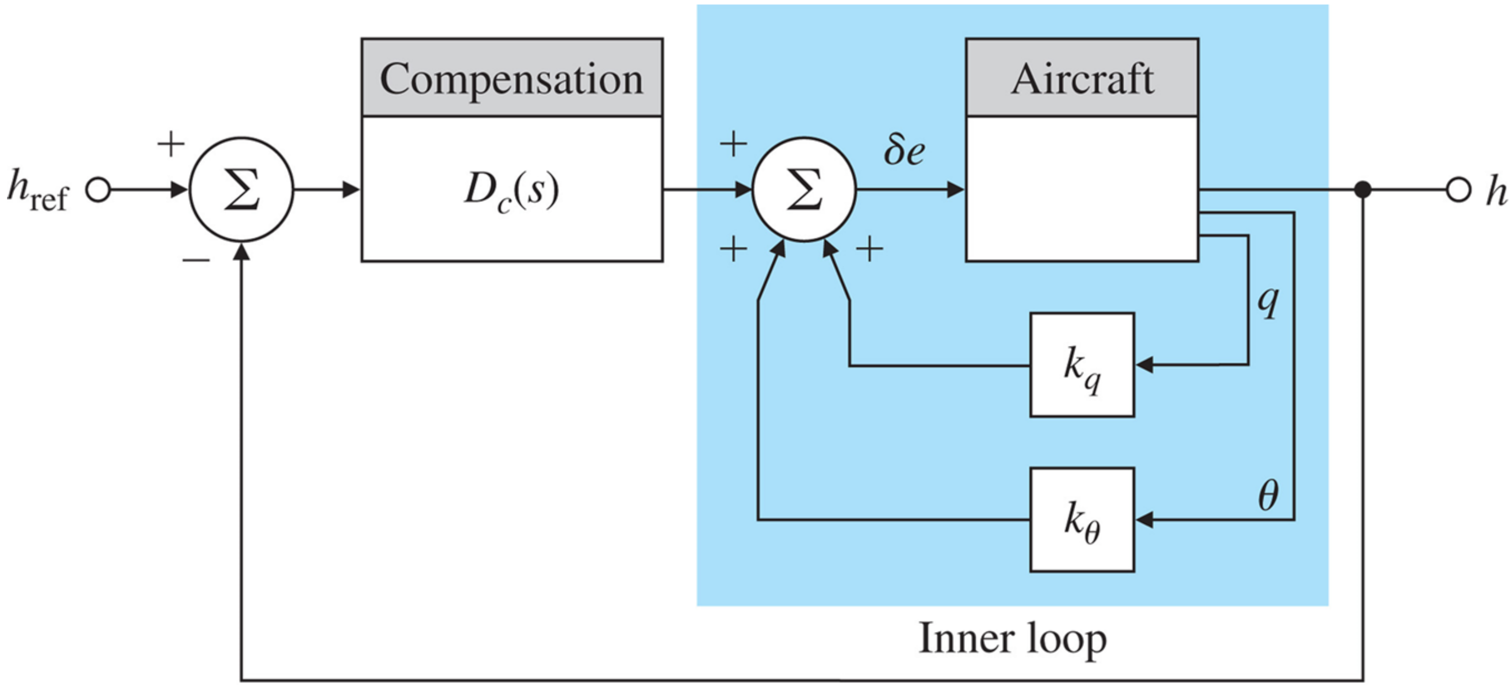


Example 10.2 Lateral and Longitudinal Control of a Boeing 747

- (STEP 4) Make a linear model

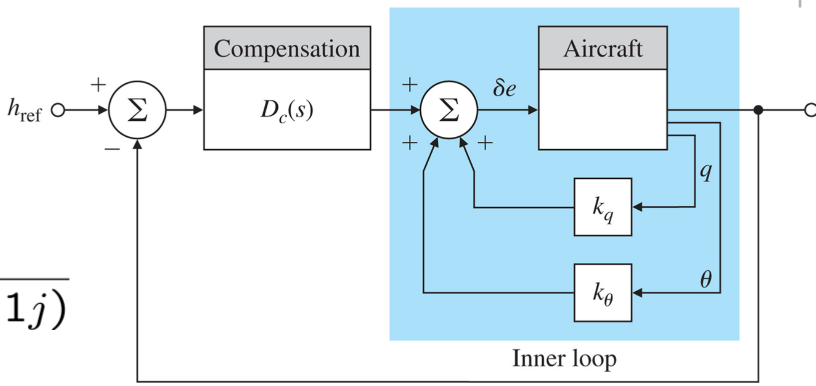
$$\frac{h(s)}{\delta e(s)} = \frac{32.7(s+0.0045)(s+5.645)(s-5.61)}{s(s+0.003\pm 0.0098j)(s+0.6463\pm 1.1211j)}$$

- (STEP 5) Try a lead-lag or PID design

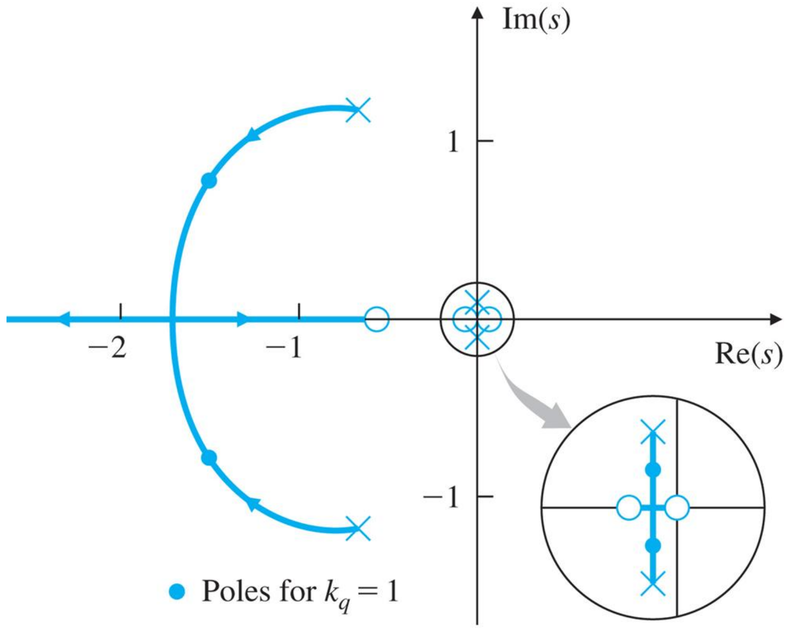


Example 10.2 Lateral and Longitudinal Control of a Boeing 747

- (STEP 5) Try a lead-lag or PID design



$$\frac{h(s)}{\delta e(s)} = \frac{2.08s(s+0.0105)(s+0.596)}{(s+0.003\pm 0.0098j)(s+0.646\pm 1.1211j)}$$



if $k_q = 1$, poles are
$-0.0039 \pm 0.0067j, -1.683 \pm 0.277j$

Example 10.2 Lateral and Longitudinal Control of a Boeing 747

- (STEP 5) Try a lead-lag or PID design
  - root locus with feedback of h and derivative of h