Automatic Flight Control Systems

- Autopilot
  - Controls a/c trajectory w/o requiring input from pilot
- Stability Augmentation System (SAS) ← adjusting stability derivatives C_{n_β}
  - Designed to improve dynamic stability
  - Relies on sensors, not on pilot inputs
- Control Augmentation System (CAS) ← adjusting control derivatives L_{δ_a}
  - Pilot input has two paths to control surfaces
    - Mechanical system
    - through the CAS electrical path
- Fly by Wire (FBW) ← choose your own derivatives
  - No mechanical link from pilot to actuators (a CAS with complete authority)

Autopilot: 1910s (A/c: Lockheed Vega (1930s))

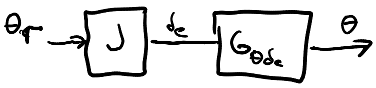
SAS (F-104) 1950s


CAS (F-15) Early '70s


FBW (F-16) Late '70s

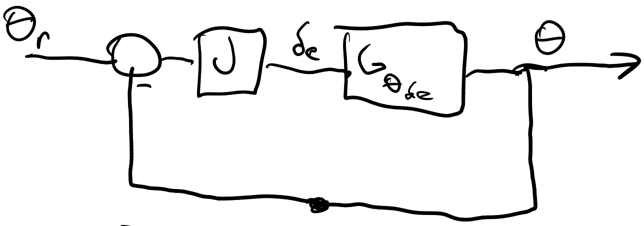
Control Design Task 1: Pitch Attitude Controller

Input: θ_r Goal: $\theta \to \theta_r$ quickly (minimal Phugoid)



$J = 1$

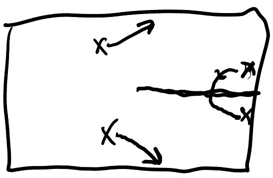
step

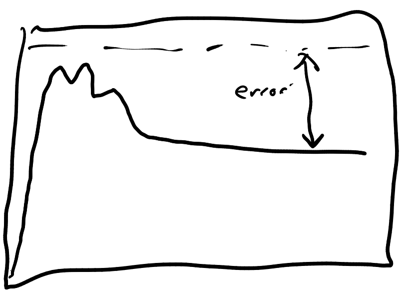


$J = K$

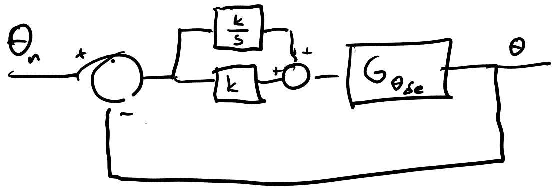
$K = -0.5$

RL

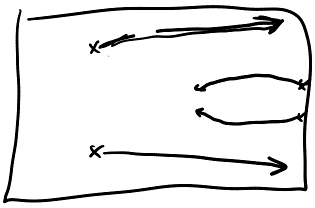




$J = K\left(1+\frac{1}{s}\right)$



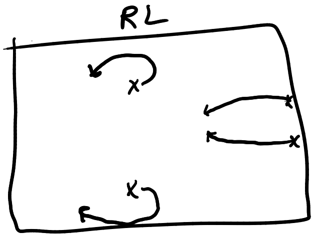
RL →



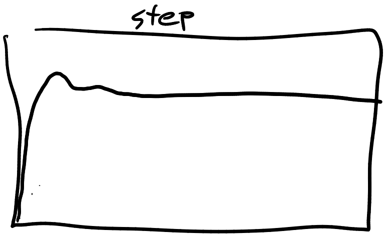
step

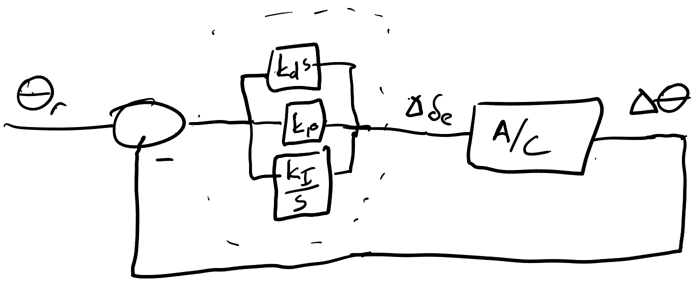
$J = K\left(1+\frac{1}{s}+s\right)$ ↗

RL



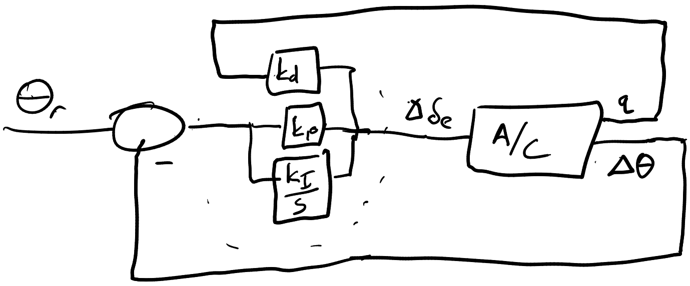
step





$\frac{d\Delta\Theta}{dt}$ very large

$\Delta\Theta$



$\Delta\delta_e = -k_p\Delta\Theta$

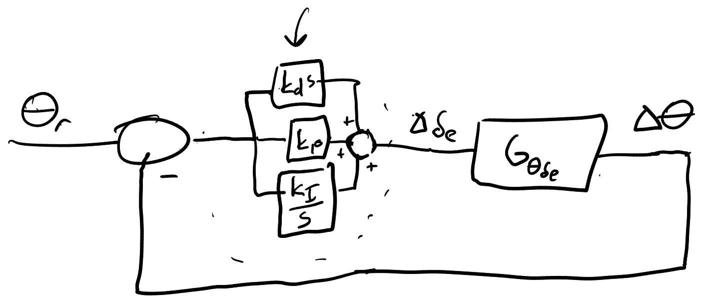
$\vec{u} = -K\vec{x}$

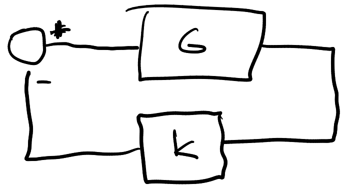
$$\begin{bmatrix}\delta_e\\ \delta_t\end{bmatrix} = -\begin{bmatrix}0&0&0&k_p\\0&0&0&0\end{bmatrix}\begin{bmatrix}\Delta u\\ \Delta w\\ q\\ \Delta\Theta\end{bmatrix}$$

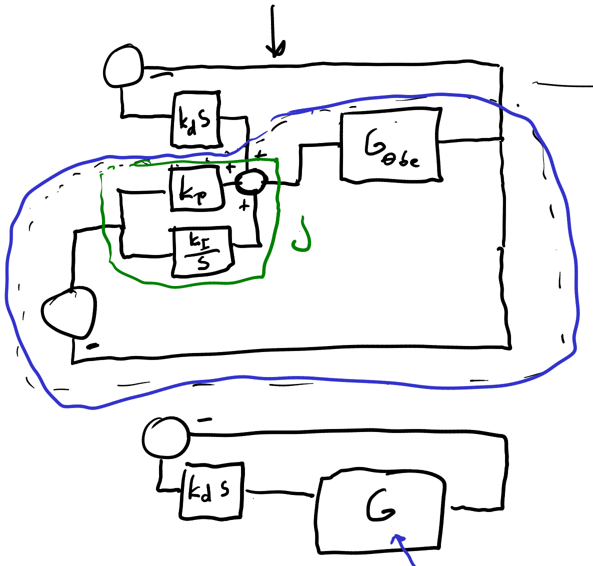
$A_{lat} - B_{lat}K$?

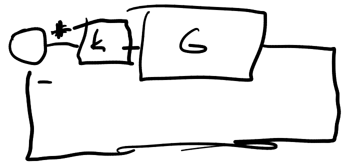
$$A_{lat} - \begin{bmatrix}0\\ -.1431\\ 0.0037\\ 0\end{bmatrix}\begin{bmatrix}0&0&0&k_p\\0&0&0&0\end{bmatrix}$$

$$A_{lat} - \begin{bmatrix}0&0&0&0\\0&0&0&-.14k_p\\0&0&0&0.0037k_p\\0&0&0&0\end{bmatrix}$$









$$G = \frac{G_{\theta\delta_e}}{1 + J\,G_{\theta\delta_e}}$$

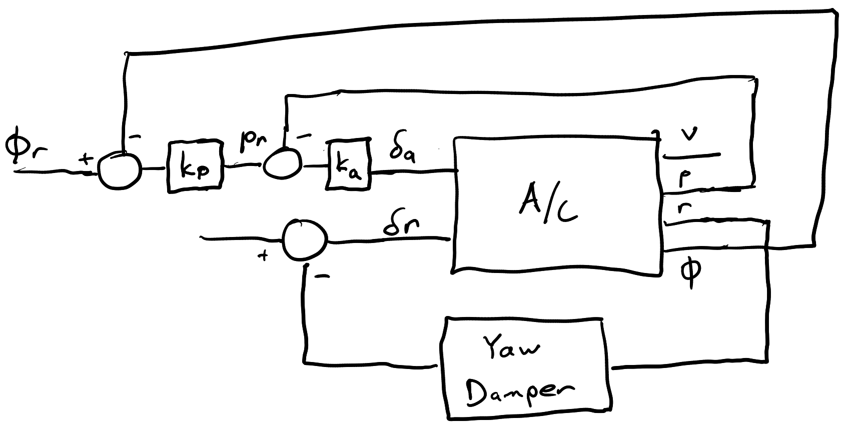
$$= \frac{G_{\theta\delta_e}}{1 + \left(k_p + \frac{k_I}{s}\right) G_{\theta\delta_e}}$$

Control Task 2: Roll Controller

Input: $\phi_r = \phi_c$ ← In Book

Goals: $\phi \to \phi_r$ quickly

Alleviate Dutch Roll



Part 1: Yaw Damper

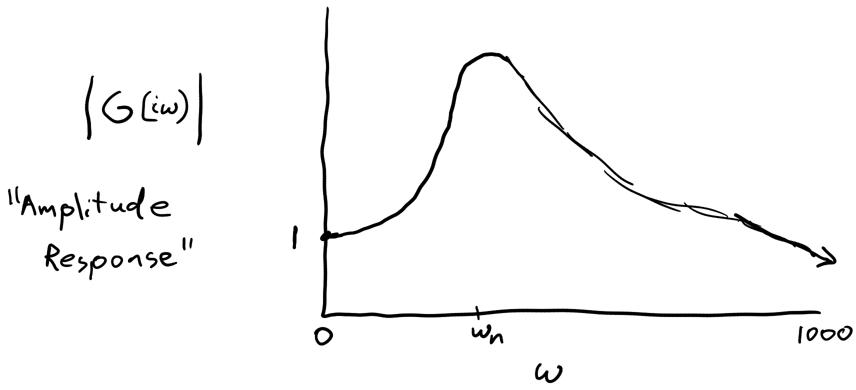
$\delta_r = -k_r r$ from RL, choose $k_r = -1.9$

Problem: In steady right turn for $k_r = -1.9$, rudder will be positive (wrong way for coordinated turn)

Want: $\delta_r \to 0$ at low frequency

$\delta_r = -k_r r$ near dutch roll freq.

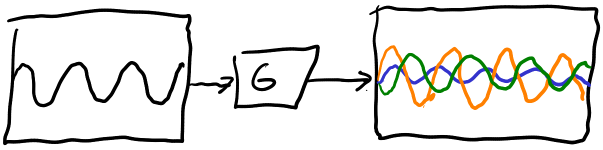
Review: Frequency Response



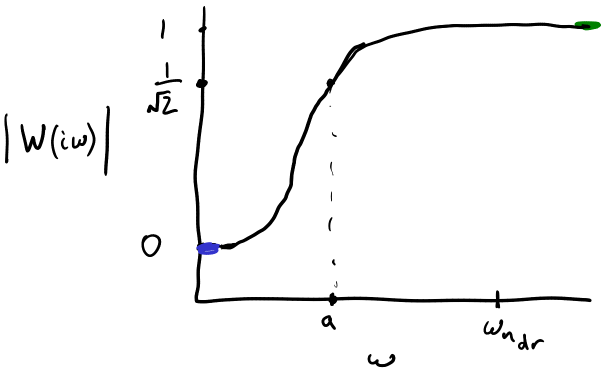
$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$$|G(0)| = 1$$

$$\lim_{\omega\to\infty} |G(i\omega)| = 0$$



"Washout" / high pass filter



$$W(s) = \frac{s}{s+a}$$

$$|W(0)| = 0$$

$$\lim_{\omega\to\infty} |W(\omega i)| = \lim_{\omega\to\infty} \left|\frac{\omega i}{\omega i}\right| = 1$$

$$|W(ai)| = \left|\frac{ai}{a+ai}\right| = \left|\frac{a e^{\frac{\pi}{2}i}}{\sqrt{2}\, a e^{\frac{\pi}{4}i}}\right| = \frac{1}{\sqrt{2}}$$

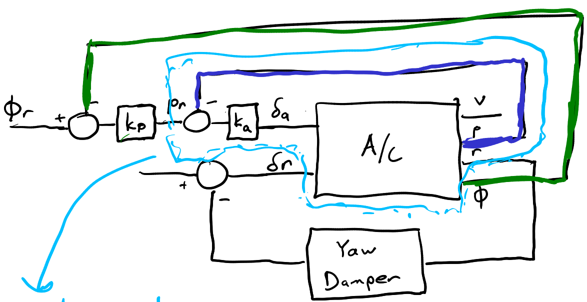
for 747 $\lambda_{dr} = -0.033 \pm 0.947i$

ω_d $\omega_{n_{dr}} \approx 1$

choose $a = 0.1$

$$\boxed{\delta_r = -k_r \frac{s}{s+0.1}}$$

Part 2: Inner and Outer loop Aileron Controller



with $k_a = -1$
this looks like 0.25

$$\delta_a = (p_r - p)\, k_a$$

$$\dot{p} = \mathcal{L}_p p + \mathcal{L}_{\delta a} \delta_a$$

$$-0.4342 = \frac{1}{\tau} \qquad -0.1431$$

$$\dot{p} = \underbrace{(\mathcal{L}_p - \mathcal{L}_{\delta a} k_a)}_{= \frac{1}{\tau_{cl}}} p + \mathcal{L}_{\delta a} k_a p_r$$

from A_{lat}
$\lambda_r = -0.5625$

at steady state, $\dot{p} = 0$

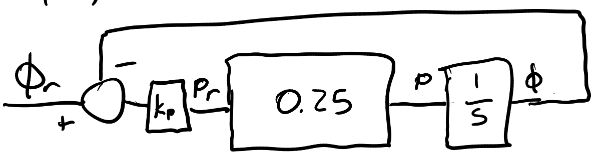
$$p_\infty = -\underbrace{\frac{\mathcal{L}_{\delta a} k_a}{\mathcal{L}_p - \mathcal{L}_{\delta a} k_a}}_{\text{Not} = 1} p_r$$

Choose $k_a = -1$

$$\hookrightarrow -\frac{\mathcal{L}_{\delta a} k_a}{\mathcal{L}_p - \mathcal{L}_{\delta a} k_a} = 0.25$$

Outer Loop

Assume: $\dot\phi = p$, roll rate dynamics (p, above) are much faster than ϕ response that we want

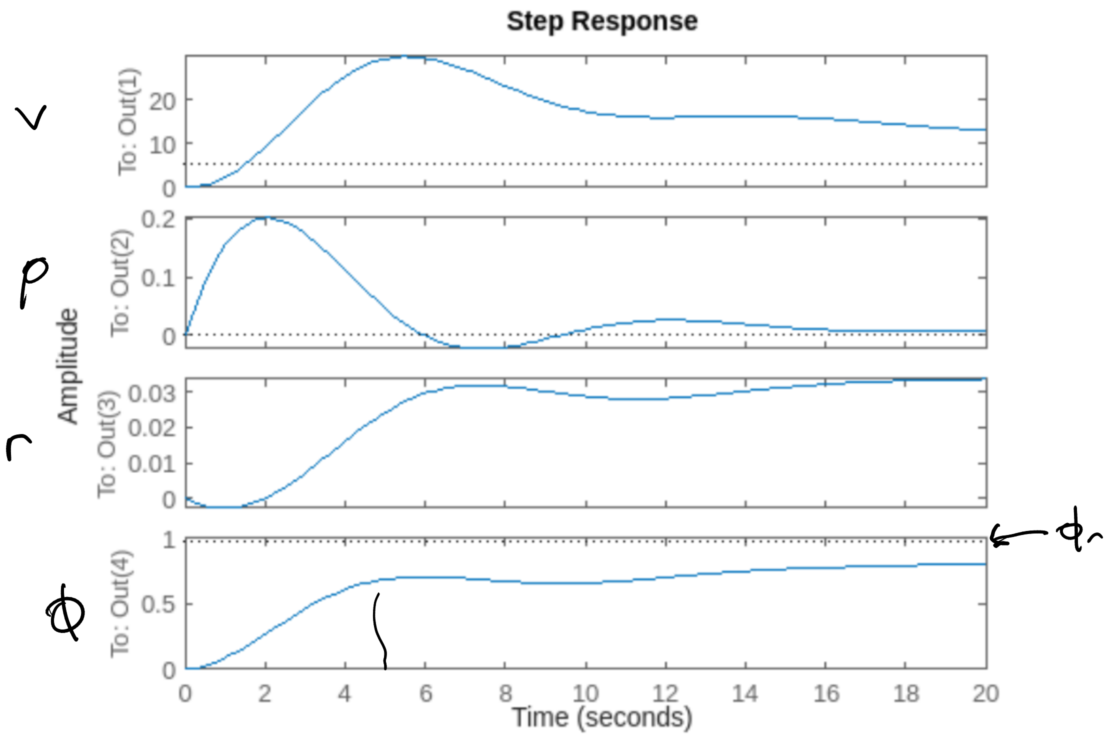


$$\dot\phi = 0.25\, k_p (\phi_r - \phi)$$

$$\dot\phi = -0.25\, k_p \phi + 0.25 k_p \phi_r$$

Based on Root Locus

choose $k_p = 1.5$



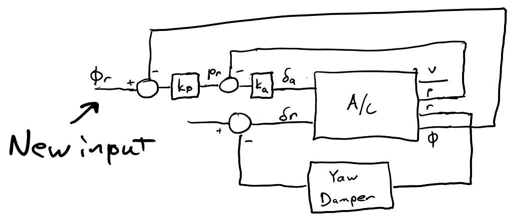
State Space Gain Matrix for this Controller (without washout)

$$\vec u = \begin{bmatrix}\delta_a \\ \delta_r\end{bmatrix} = -K\vec x = -\underbrace{\begin{bmatrix}0 & k_a & 0 & k_a k_p \\ 0 & 0 & k_r & 0\end{bmatrix}}_{K}\begin{bmatrix}v \\ p \\ r \\ \phi\end{bmatrix}$$

$$\delta_a = -k_a p + k_a p_r$$

$$= -k_a p - k_a k_p \phi$$

$$\delta_r = -k_r r$$



$$A_{roll} = A_{lat} - B_{lat} K$$

$$\dot{\vec{x}} = A_{roll} \vec{x} + \underbrace{B_{lat} \begin{bmatrix} k_p k_a \\ 0 \end{bmatrix}}_{B_{roll}} \phi_c$$