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Q1

Q

a)

$$\tilde{G}_1(s) = \frac{k(z_3 s + 1) e^{-\Theta s}}{(z_1 s + 1)(z_2 s + 1)}$$

a)

$$\tilde{G}_1(s) = \tilde{G}_1^+(s) \cdot \tilde{G}_1^-(s)$$

$$G_{1c}^*(s) = \frac{1}{z_1 s + 1} \cdot \tilde{G}_1^-(s)$$

$$G_1(s) = \frac{G_{1c}^*(s)}{1 - G_{1c}^*(s) \tilde{G}_1(s)} = \frac{(\tilde{G}_{1c}^-(s))^{-1} F}{1 - (\tilde{G}_{1c}^-(s))^{-1} F \tilde{G}_1^+(s) \cdot \tilde{G}_1^-(s)}$$

$$= \frac{\tilde{G}_{1c}^-(s) F}{(\tilde{G}_{1c}^-(s)) [1 - F \tilde{G}_1^+(s)]}$$

Substituting.

$$G_1(s) \neq \tilde{G}_1^+(s) = e^{-\Theta s}$$

$$\tilde{G}_1^-(s) = \frac{k(z_3 s + 1)}{(z_1 s + 1)(z_2 s + 1)}$$

$$G_1(s) = \frac{1}{\left( \frac{(z_1 s + 1)(z_2 s + 1)}{k(z_3 s + 1)} \right) \left[ 1 + z_1 s - e^{-\Theta s} \right]}$$

$$e^{-\Theta s} \approx 1 - \Theta s$$

$$G_1(s) = \frac{k(z_3 s + 1)}{(z_1 s + 1)(z_2 s + 1)} \frac{1}{(z_1 + \Theta)s} \frac{k(z_1 s + 1)(z_2 s + 1)}{k(z_3 s + 1)(z_1 + \Theta)s}$$

$$= \frac{1}{k(z_1+s)} \cdot (z_1+z_2-z_3) \left[ \frac{(z_1s+1)(z_2s+1)}{(z_2s+1)s - (z_1+z_2-z_3)} \right]$$

$$\begin{matrix} z_1 \\ z_2 \\ z_3 \end{matrix}$$

$$Q_1 \quad b) \quad \frac{k(z_3 s + 1) e^{-\theta s}}{\tau^2 s^2 + 2 \zeta z s + 1}$$

$$\tilde{G}_1^+(s) = e^{-\theta s}$$

$$\tilde{G}_1^-(s) = \frac{k(z_3 s + 1)}{\tau^2 s^2 + 2 \zeta z s + 1}$$

$$F = \frac{1}{z_c s + 1}$$

$$G_c = \frac{G_c^+}{1 - G_c^- \tilde{G}_1^-} \rightarrow \frac{\tilde{G}_1^- F}{1 - \tilde{G}_1^- F \tilde{G}_1^+}$$

$$\frac{\tau^2 s^2 + 2 \zeta z s + 1}{k(z_3 s + 1) \left[ 1 - (1 - \theta s) \right] \left[ 1 + z_s - (1 - \theta s) \right]}$$

$$\Rightarrow \frac{1}{k(1 - \theta s)} \frac{\tau^2 s^2 + 2 \zeta z s + 1}{s(z_3 s + 1)}$$

(Q2)  $G(s) = \frac{1}{(s+1)(0.2s+1)(0.04s+1)(0.008s+1)}$

a) i) SOPTD  $\frac{ke^{-\theta s}}{(z_1 s + 1)(z_2 s + 1)}$

target neglected time constant in denominator = 0.04

$$\therefore \theta = 1 + \frac{0.04}{2} + 0.008 = 0.028$$

$$z_1 = 1$$

$$k=1$$

$$z_2 = 0.2 + \frac{0.04}{2} = 0.22$$

$$\tilde{G}(s) = \frac{-0.028s}{(s+1)(0.22s+1)}$$

taking condition I from table 12.1, with  $z_3 = 0$

$$K_L = \frac{z_1 + z_2 - z_3}{k(z_L + \theta)} = \frac{1.22}{z_L + 0.028}$$

$$z_L = z_1 + z_2 - z_3 = 1.22$$

$$z_b = \frac{z_1 z_2 - (z_1 + z_2 - z_3) z_3}{z_1 + z_2 - z_3} = 0.18$$

for  $z_L = 0.148$  as  $\theta/z_1 = 0.248 < 0.5$  hence  $z_L = FOPTD \odot$   
i.e default value, table 12.3  $\Rightarrow K_L = \underline{\underline{6.93}}$

Q2 a) ii)

FOPDT

$$\frac{ke^{-\theta s}}{(z_1 s + 1)}$$

largest neglected time const = 0.2

$$\Theta = 1 + 0.008 + 0.04 + 0.2/2 = 0.148$$

$$z_1 = 1 + 0.2/2 = 1.1$$

$$K=1$$

$$G_1(s) = \frac{e^{-0.148s}}{1.1s + 1}$$

$$K_L = \frac{1}{k} \left( 0.2 + 0.4s \frac{z_1}{\Theta} \right) = 0.3 \frac{s}{4}$$

$$z_I = \frac{0.4\Theta + 0.6z_1\Theta}{\Theta + 0.12} = 0.54$$

$$z_D = \frac{0.5\Theta z_1}{0.3\Theta + z_1} = 0.071$$

$$0.5\Theta + z_1 = 0.5 + 0.5 = 1$$

$$0.5\Theta^2 + 1.5\Theta + 0.5 = 0.5\Theta^2 + 0.5$$

neglecting 0.5 and 1.5 we get 0.5 = 0.5

so 0.5 = 0.5 which is correct

Q3

Q2) a) iii)

$$\theta = 0.148$$

$$z = 1.1$$

$$k = 1$$

$$Y = A(\theta/z)^B$$

$$\text{for P, } Y = 9.0686$$

$$\text{for I, } Y = 3.7$$

$$\text{for D, } Y = 0.0518$$

for Disturbance.

10% + 30% = 30%

10% + 30% = 40%

10% + 30% = 50%

10% + 30% = 60%

10% + 30% = 70%

10% + 30% = 80%

10% + 30% = 90%

10% + 30% = 100%

10% + 30% = 110%

10% + 30% = 120%

10% + 30% = 130%

10% + 30% = 140%

10% + 30% = 150%

10% + 30% = 160%

10% + 30% = 170%

10% + 30% = 180%

10% + 30% = 190%

10% + 30% = 200%

10% + 30% = 210%

10% + 30% = 220%

10% + 30% = 230%

10% + 30% = 240%

10% + 30% = 250%

10% + 30% = 260%

10% + 30% = 270%

10% + 30% = 280%

10% + 30% = 290%

10% + 30% = 300%

10% + 30% = 310%

10% + 30% = 320%

10% + 30% = 330%

10% + 30% = 340%

10% + 30% = 350%

10% + 30% = 360%

10% + 30% = 370%

10% + 30% = 380%

10% + 30% = 390%

10% + 30% = 400%

10% + 30% = 410%

10% + 30% = 420%

10% + 30% = 430%

10% + 30% = 440%

10% + 30% = 450%

10% + 30% = 460%

10% + 30% = 470%

10% + 30% = 480%

10% + 30% = 490%

10% + 30% = 500%

10% + 30% = 510%

10% + 30% = 520%

10% + 30% = 530%

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10% + 30% = 1080%

10% + 30% = 1090%

10% + 30% = 1100%

10% + 30% = 1110%

10% + 30% = 1120%

10% + 30% = 1130%

10% + 30% = 1140%

10% + 30% = 1150%

10% + 30% = 1160%

10% + 30% = 1170%

10% + 30% = 1180%

10% + 30% = 1190%

10% + 30% = 1200%

10% + 30% = 1210%

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10% + 30% = 1300%

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10% + 30% = 1370%

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10% + 30% = 1490%

10% + 30% = 1500%

10% + 30% = 1510%

10% + 30% = 1520%

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10% + 30% = 1570%

10% + 30% = 1580%

10% + 30% = 1590%

10% + 30% = 1600%

10% + 30% = 1610%

10% + 30% = 1620%

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10% + 30% = 1980%

10% + 30% = 1990%

10% + 30% = 2000%

10% + 30% = 2010%

10% + 30% = 2020%

10% + 30% = 2030%

10% + 30% = 2040%

10% + 30% = 2050%

10% + 30% = 2060%

10% + 30% = 2070%

10% + 30% = 2080%

10% + 30% = 2090%

10% + 30% = 2100%

10% + 30% = 2110%

10% + 30% = 2120%

10% + 30% = 2130%

10% + 30% = 2140%

10% + 30% = 2150%

10% + 30% = 2160%

10% + 30% = 2170%

10% + 30% = 2180%

10% + 30% = 2190%

10% + 30% = 2200%

10% + 30% = 2210%

10% + 30% = 2220%

10% + 30% = 2230%

10% + 30% = 2240%

10% + 30% = 2250%

(Q 2) a) iv)

from tweaking on Simulink,

$$K_{cu} = 30.1$$

$$P_{cu} = 417$$

$$\therefore K_c = 0.6 K_{cu} = 18.06$$

$$\tau_I = P_{cu} / 2 = 0.28$$

$$\tau_D = P_{cu} / 8 = 0.071$$

b) Implemented on Simulink.

c) IMC settings provide the best result.

AMIGO most conservative

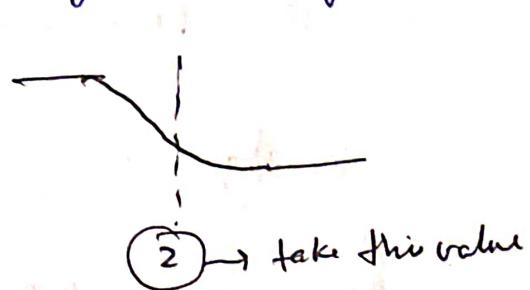
ITAE & ZN settings are the most aggressive

& produce damped oscillatory response.

AMIGO also produces damped oscillatory response.

Q3 phase diagram indicates the presence of time delay.

(tail approaches infinity)



$$R \text{ AR}_{OL} \Big|_{\omega=0.01} = 3 \Rightarrow k = 3 \times 0.01 = 0.03$$

At  $\omega = 0.1$ , slope increases,  $\Rightarrow$  real zero  $\left(\frac{s}{0.1} + 1\right)$

At  $\omega = 20^\circ$ , slope decreases,  $\Rightarrow$  real pole  $\Rightarrow \frac{s}{20} + 1$

At  $\omega = 20^\circ$ , slope decreases  $\Rightarrow$  real pole  $\Rightarrow \left(\frac{s}{20} + 1\right)$

$$\begin{array}{c} (\frac{10s}{0.1} + 1) \\ \cancel{(s+1)} \\ (s+1)(\frac{s}{10} + 1) \end{array}$$

this implies, there are two real poles & 1 real zero  
the phase starts from  $-90^\circ$  implies presence of  $s$  in denominator

$$\frac{k(z_a s + 1)}{s(z_b s + 1)(z_c s + 1)} \quad \therefore z_a = 1/0.1 \\ z_b = 1/2 \\ z_c = 1/20$$

$$\therefore G(s) = \frac{150.03(10s + 1)}{s(0.5s + 1)(0.05s + 1)}$$

b)

Q3

Q3

b)  $\phi_g = PM - 180^\circ = 30 - 180^\circ = -150^\circ$

for  $\phi_g = -150^\circ$ ,  $\omega_g \approx 38.93 \text{ rad/s}$

At  $\omega = \omega_g \quad \frac{AR_{OL}}{K_C} = 0.007$

$AR_{OL} |_{\omega=\omega_g} = 1$

$\therefore K_C = 1 / 0.007 = 142.86$

$\omega_c$  is not defined for this  
hence ~~Phase Margin~~ Gain Margin is not applicable.

Q4)

a)  $G_{OL} = \frac{1}{(4s+1)(2s+1)} \cdot k_c$

Second order transfer function, the phase approaches  $-180^\circ$  but never attains it, hence the system is stable for all values of  $k_c$  i.e. can't be unstable.

b)  $G_{OL} = \frac{1}{(4s+1)(2s+1)} \cdot k_c \frac{(5s+1)}{ss}$

$$\left. \begin{aligned} & +90 - 90 - 90 - 90 \\ & = -180^\circ \end{aligned} \right\}$$

$$\phi = -\tan^{-1}(4\omega) - \tan^{-1}(2\omega) + \tan^{-1}(5\omega) - \pi/2 \rightarrow \text{min value} = -180^\circ$$

Never attains phase angle  $-180^\circ$ , hence stable, can't be unstable

c)  $G_{OL} = \frac{s+1}{(4s+1)(2s+1)} \cdot k_c \frac{(2s+1)}{s}$

$$\phi = \tan^{-1}(\omega) + \tan^{-1}(2\omega) + \tan^{-1}(4\omega) + \tan^{-1}(2\omega) - \pi/2$$

$$\min(\phi) = +90 + 90 - 90 - 90 - 90 \times -90^\circ$$

Never attains  $-180^\circ$ , hence system is stable, can't be unstable

$$Q_4) \text{ d) } G_{OL} = \frac{1-s}{k_c}$$

$$(4s+1)(2s+1)$$

$$\phi = \tan^{-1}(-\omega) - \tan^{-1}(4\omega) + \tan^{-1}(2\omega)$$

$$\min(\phi) \approx -290^\circ$$

attains phase of  $-180^\circ$ , hence the system can be unstable for large values of  $k_c$

e)

$$G_{OL} = \frac{e^{-s}}{4s+1} \cdot k_c$$

$$\phi = -\tan^{-1}(4\omega) + \tan^{-1}\left(-\frac{\sin\omega}{\cos\omega}\right)$$

$$= -\tan^{-1}(\omega/4\omega) - \omega$$

$$\min(\phi) \rightarrow 0$$

$\therefore$  System can be unstable due to time delay at high frequencies. (~~when it attains  $180^\circ$~~ )

$$Q5 \quad G_C = K_C \left( \frac{2s+1}{0.1s+1} \right) \quad G_P = \frac{0.4}{s(ss+1)}$$

$$G_V = \frac{2}{0.5s+1} \quad G_D = \frac{3}{ss+1}$$

$$G_M = 1$$

a)  $G_{OL} = G_C G_V G_P G_M = K_C \left( \frac{2s+1}{0.1s+1} \right) \left( \frac{0.4}{s(ss+1)} \right) \left( \frac{2}{0.5s+1} \right) \cdot 1$

$$AR_{OL}(\omega_c) = |G_{OL}(j\omega_c)| \leq 1$$

$$\Rightarrow K_C \frac{\sqrt{4\omega^2 + 1}}{\sqrt{0.01\omega^2 + 1}} \cdot \frac{0.4}{\omega \sqrt{0.02s\omega^2 + 1}} \cdot \frac{2}{\sqrt{0.2s\omega^2 + 1}}$$

$$\phi_{OL}(\omega_c) = \angle G_{OL}(j\omega_c) = -188^\circ$$

$$\phi = 0 + \tan^{-1}(2\omega) + 0 + 0 - \tan^{-1}(0.1\omega) - \pi/2 - \tan^{-1}(5\omega) \\ - \tan^{-1}(0.5\omega)$$

$$G_{OL} = \frac{K_C (1.6s + 0.8)}{\frac{s^4}{4} + \frac{61s^3}{20} + \frac{28s^2}{5} + s}$$

b)  $\phi_g = PM - 180^\circ = 30^\circ - 180^\circ = -150^\circ$

for  $\phi_g = -150^\circ$ ,  $\omega_g = 1.72 \text{ rad/min}$

$1.71822 \approx 1.72 \text{ rad/min}$

$$\therefore \text{At } \omega = \omega_g, \frac{AR_{OL}}{K_C} = \frac{-16.8645}{exp} = 0.144 \quad \therefore AR_{OL}(\omega = \omega_g) = 1 \\ K_C = 1/0.144 = 6.94$$

Q5

c) for  $\phi = -180^\circ$ ,  $\omega_c = 4.06 \text{ rad/s}$ 

$$\frac{A_{ROL}}{k_c} \Big|_{\omega=\omega_c} = 0.0325$$

$$A_C = A_{ROL} \Big|_{\omega=\omega_c} = 0.325$$

$$GM = 1/A_C = 3.08$$

ii) a)  $G_{ROL} = \frac{k_c (1.6s + 0.8)}{\frac{s^4}{4} + \frac{G_1 s^3}{20} + \frac{20 s^2}{5} + s} e^{-s}$

$$e^{-s} \quad e^{-j\omega} = \cos \omega - j \sin \omega$$

AR<sub>OL</sub> : same as before

$$\Phi_{ROL} = \tan^{-1}(2\omega) - \tan^{-1}(0.1\omega) - \pi/2 - \tan^{-1}(5\omega) - \tan^{-1}(0.5\omega) + \tan^{-1}\left(-\frac{\sin \omega}{\cos \omega}\right)$$

b)  $\omega_g$  for  $\phi_g = -180^\circ = 0.38 \text{ rad/s}$

$$\text{At } \omega = \omega_g, \frac{A_{ROL}}{k_c} = 1.19$$

$$\therefore A_{ROL} \Big|_{\omega=\omega_g} = 1$$

$$k_c = 1 / 1.19 = 0.84$$

c) for  $\phi = -180^\circ$ ,  $\omega_c = 0.8 \text{ rad/s}$ 

$$\frac{A_{ROL}}{k_c} \Big|_{\omega=\omega_c} = 0.42$$

$$A_C = A_{ROL} \Big|_{\omega=\omega_c} = 4.2$$

$$GM = 1/A_C = 0.24$$

$$\underline{Q_6} \quad G_{ip}(s) = \frac{e^{-s}}{s+1}$$

$$G_{id}(s) = \frac{2}{(s+1)(ss+1)}$$

$$G_{iv} = G_{im} = G_t = 1$$

$$a) \quad G_f = -\frac{G_{id}}{G_t G_v G_{ip}}$$

for steady state conditions,

$$G_{ip} = k_p = 1$$

$$G_{id} = k_u = 2 \quad = -\frac{2}{1 \cdot 1 \cdot 1} = -2$$

$$G_{iv} = G_{im} = G_t = 1$$

$$G_f = -2$$

b) Dynamic Analysis

$$G_f = -\frac{G_{id}}{G_{iv} G_t G_{ip}} \Rightarrow -\frac{2}{(s+1)(\cancel{ss+1})}$$

$$(1)(1) \frac{e^{-s}}{(s+1)}$$

$$\rightarrow \frac{2}{(ss+2)(s+1)} e^{+s} \cdot (s+1) \quad \text{from Example 15.3}$$

$$\approx 2 \frac{(1+1)s+1}{(ss+2)(s+1)} \rightarrow -\frac{2(2s+1)}{(ss+1)(s+1)}$$

Q6

c)  $\tilde{G}_1 = G_{1v} G_{1f}, G_{1v} = \frac{e^{-s}}{s+1}$        $\begin{matrix} \theta=1 \\ z=1 \end{matrix}$        $k=1$   
 $G_{1f} = \frac{1}{s+2}$        $\begin{matrix} \theta=2 \\ z=2 \end{matrix}$

from table 12.1,  $\underline{G_1}$

taylor       $k_L = \frac{1}{z_L + \theta} \quad z_L = 2 \quad z_0 = -$

$k_L = \frac{1}{3} \quad z_L = 1$

$$G_L = \frac{1}{3} \left[ 1 + \frac{1}{s} \right] = \frac{s+1}{3s}$$

d)  $G_L = 0$        $D' \cdot d(t) = u(t)$

$D(s) = 1/s$

Closed loop

$$\begin{matrix} 10s - 10s^2 \\ +2 - 2s \\ +10^3 - 2s - 2 \end{matrix}$$

$$Y = G_{1d} D + [G_{1f} G_{1v} G_{1f} G_L] D$$

$$= \frac{2}{(s+1)(5s+1)s} + \left[ \frac{e^{-s}}{s+1} \cdot 1 \cdot (-2) \cdot (1) \right] \cdot \frac{1}{s}$$

$$Y(s) = \frac{2 + -2(5s+1)e^{-s}}{(s+1)(5s+1)e^{-s}} = \frac{2 - (10s+2)e^{-s}}{(s+1)(5s+1)e^{-s}}$$

$$e^{-s} \approx 1 - \theta \text{ if } s = \frac{2 - (10s+2)(1-s)}{(s+1)(5s+1)(s)} \Rightarrow \frac{10s^2 - 8s}{(s+1)(5s+1)(s)} \Rightarrow \frac{10s - 8}{(s+1)(5s+1)}$$

Q6 d)  $Y(s) = \frac{10s - 8}{(s+1)(5s+1)}$

$$y(t) = L^{-1} \left\{ \frac{9}{2(s+1)} - \frac{2s}{2(5s+1)} \right\} = \frac{9}{2} e^{-t} - \frac{2s}{2} e^{-2s+1/5}$$

$$= \frac{1}{2} [9e^{-t} - 2se^{-t/5}]$$

Now for  $G_f = \frac{-2(2s+1)}{(s+1)(5s+1)(s+1)}$

$$Y = \left( \frac{2}{(s+1)(5s+1)} + \frac{e^{-s}}{(s+1)} \cdot 1 \cdot \left( \frac{-2(2s+1)}{(5s+1)(s+1)} \right) \right) \frac{1}{s}$$

$$= \frac{2s+2 - 2e^{-s}(2s+1)}{(s+1)(5s+1)(s+1)s}$$

taylor approximation

$$e^{-s} \approx (1-s)$$

$$Y(s) = \frac{2s+2 - 2(1-s)(2s+1)}{(s+1)^2(5s+1)s} = \frac{4s^2}{(s+1)^2(5s+1)s}$$

$$y(s) = L^{-1} \left\{ \frac{4s}{(s+1)^2(5s+1)} \right\} = L^{-1} \left\{ \frac{1}{4(s+1)} + \frac{1}{(s+1)^2} - \frac{5}{4(5s+1)} \right\}$$

$$= \frac{1}{4} e^{-t} + e^{-t} t - \frac{1}{4} e^{-t/5}$$

$$(Q6) e) \quad G_L \neq 0 \quad G_C = \frac{S+1}{3S}$$

$$\frac{Y}{D} = \frac{G_d + G_t G_f G_{uv} G_{lp}}{1 + G_c G_{lp} G_m G_{uv}}$$

$y$  for (a) (c) :  $G_f \lambda = (-2)$

$$Y(s) = \frac{\frac{2}{(s+1)(5s+1)} + \frac{e^{-s}(-2)}{s+1}}{1 + \frac{s+1}{3s} \cdot 1 \cdot \frac{e^{-s}}{s+1}}$$

$$e^{-s} \approx (1-s)$$

$$= \frac{2 - 2(1-s)(5s+1)}{(s+1)(5s+1) [3s(8s+3) + (8s+1)(1-s)]}$$

$$Y(s) \Rightarrow \frac{(10s^2 - 8s)3s}{(s+1)(5s+1)(2s+1)} \cdot \frac{1}{s}$$

$$y(t) = L^{-1}(Y(s)) = 3\delta(t) - \frac{27}{2}e^{-t} + \frac{13}{2}e^{-t/2} - \frac{1}{2}e^{-t/5}$$

$$Y(t) = L^{-1} \left\{ \frac{27}{2(s+1)} - \frac{26}{12(s+1)} + \frac{25}{2(5s+1)} \right\} = \frac{27}{2}e^{-t} - 13e^{-t/2} + 5/2e^{-t/5}$$

Q6) e) (b) & (c)

$$Y(s) = \frac{\frac{2}{(s+1)(ss+1)} + \frac{e^{-s}}{s+1} \cdot \frac{-2(2s+1)}{(ss+1)(s+1)}}{1 + \frac{s+1}{3s} \cdot 1 \cdot \frac{e^{-s}}{s+1}}$$

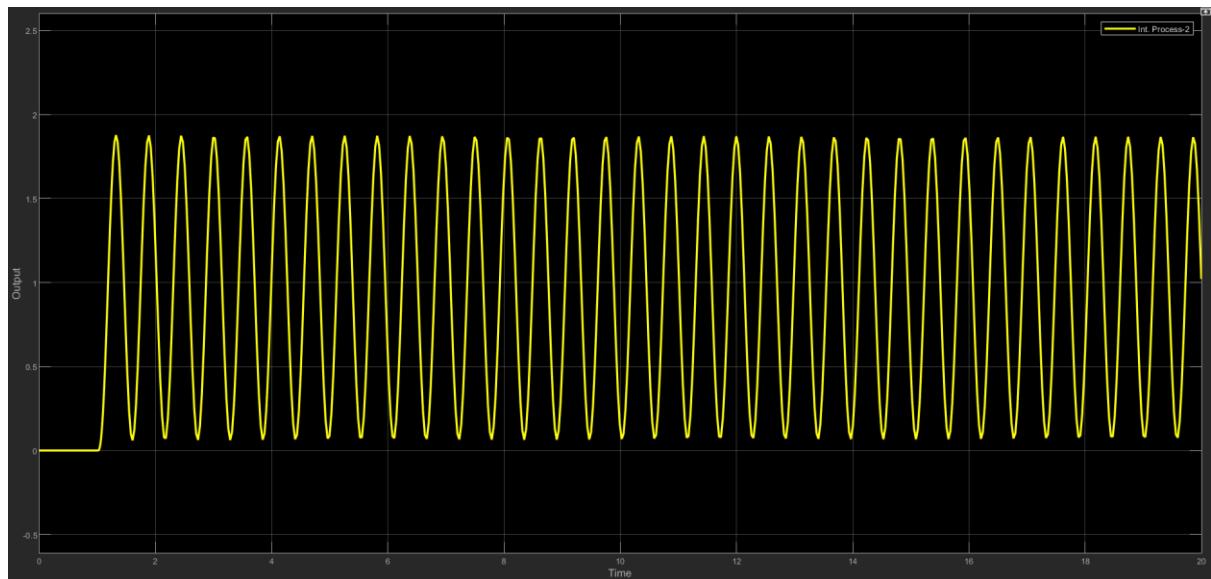
$$Y(s) = \frac{\frac{4s}{(s+1)^2(ss+1)} \cdot 3s' \cdot \frac{1}{s'}}{3s + 1 - s}$$

$$y(t) = L^{-1} \left\{ -\frac{27}{4} \cdot \frac{1}{s+1} - \frac{3}{(s+1)^2} - \frac{2s}{4(ss+1)} + \frac{16}{2s+1} \right\}$$

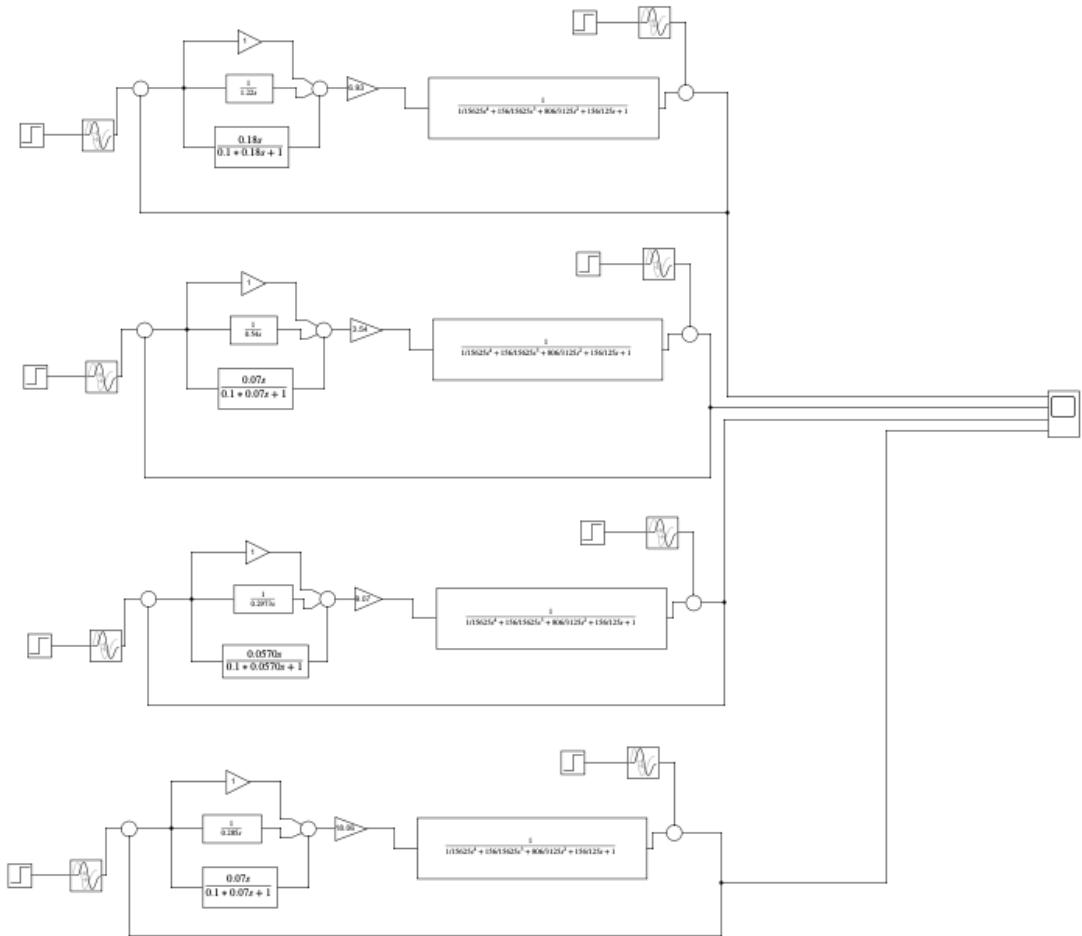
$$= -\frac{27}{4} e^{-t} - \cancel{3e^{-t}t} - 3e^{-t}t - \frac{2s}{4} e^{-t/5} + 8e^{-t/2}$$

Q1) Refer paper notes

Q2) a) iv)



Q2) b)



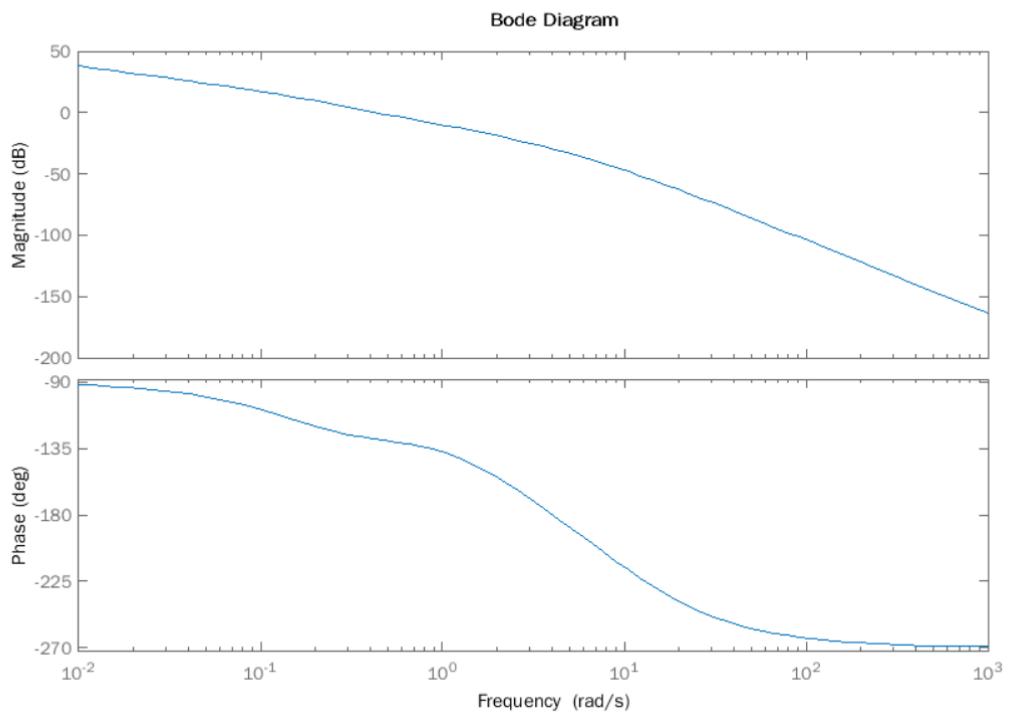
Q3)

In paper

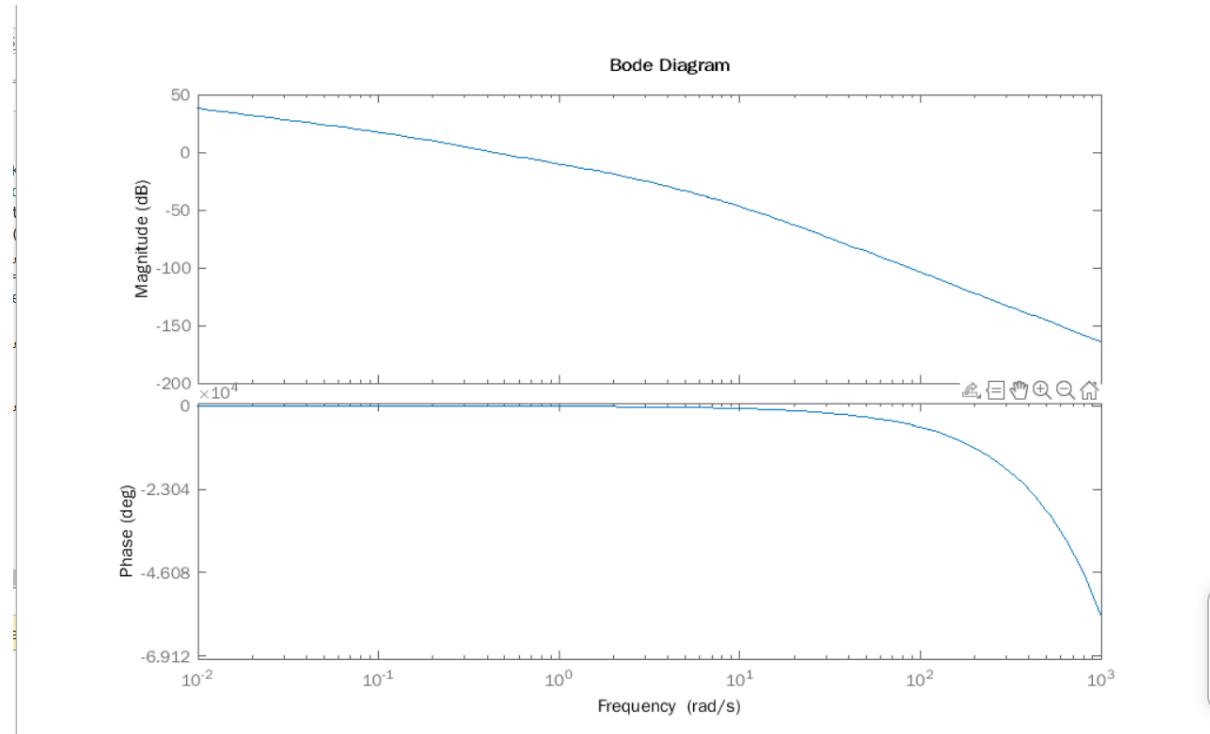
Q4)

In paper

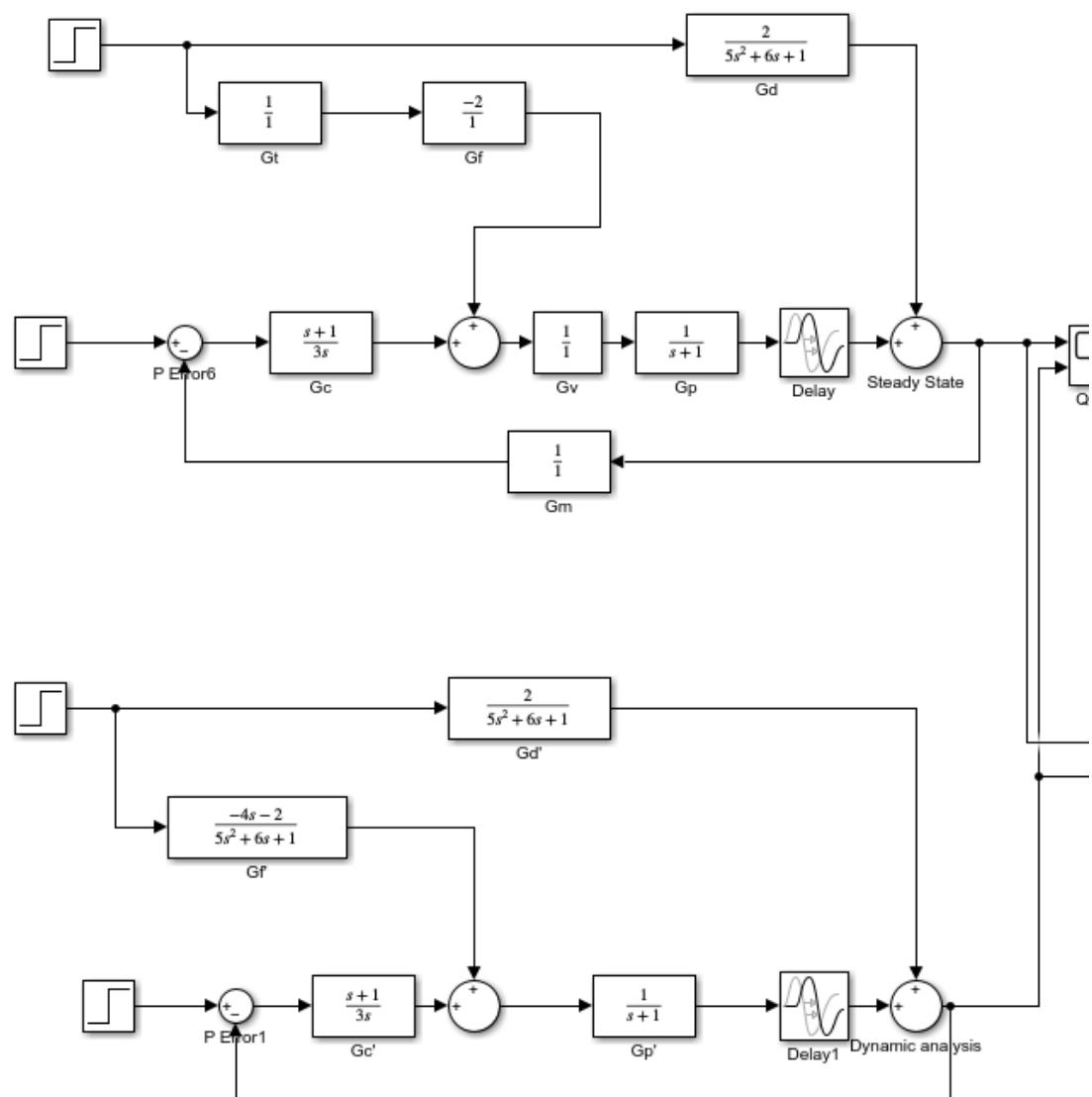
Q5) for normal

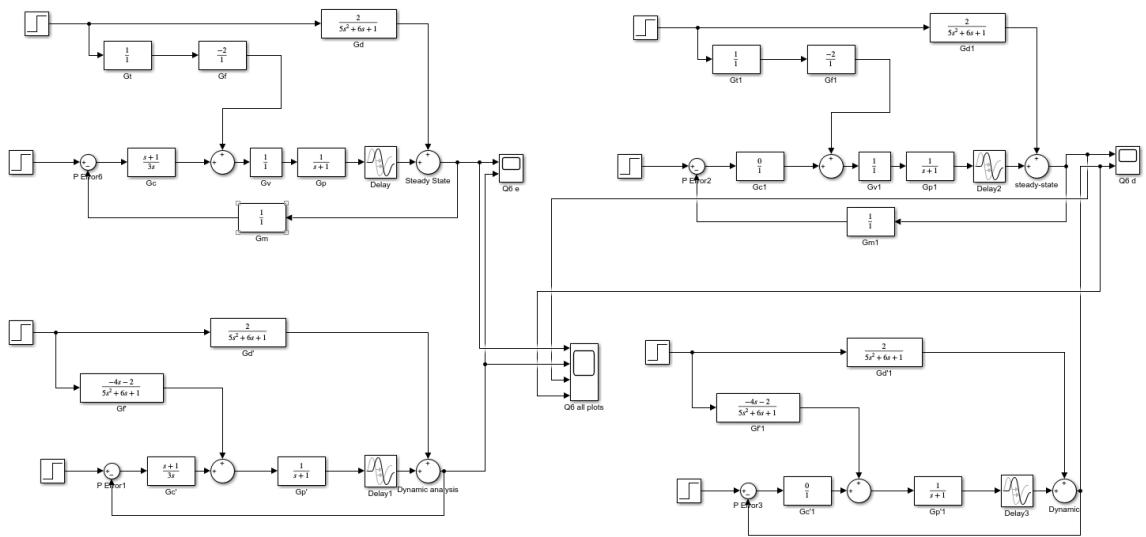


For time delay

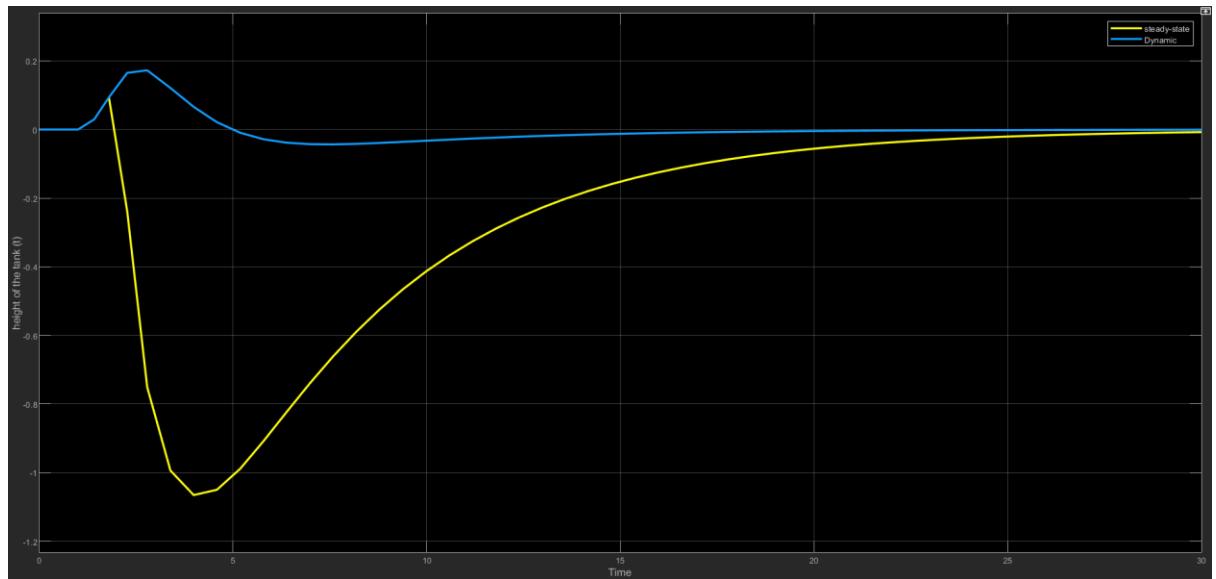


Q6)

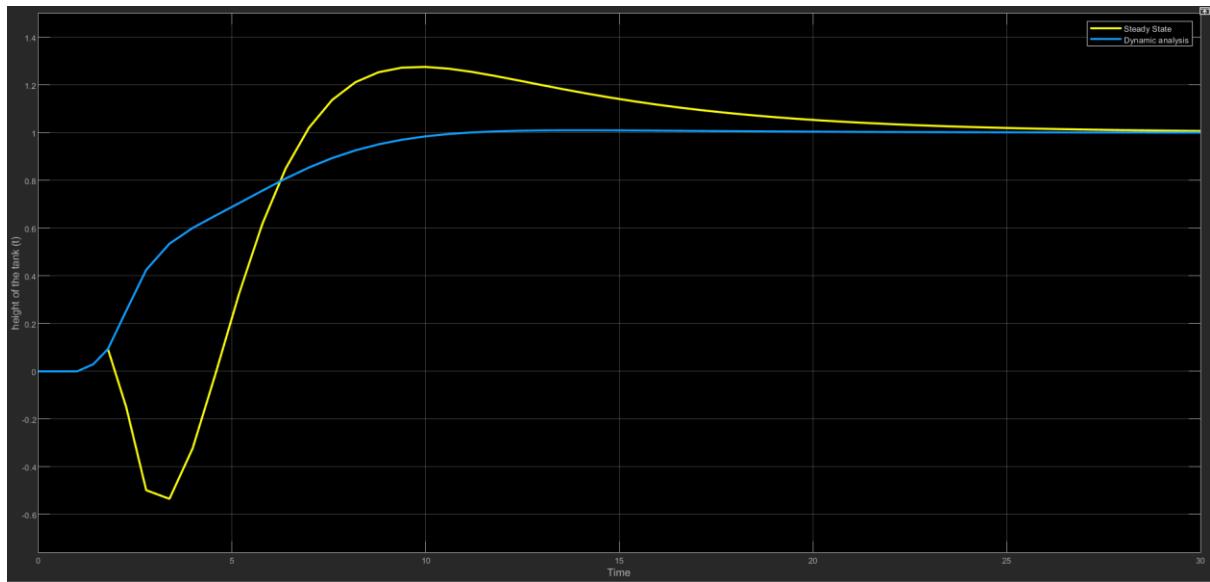




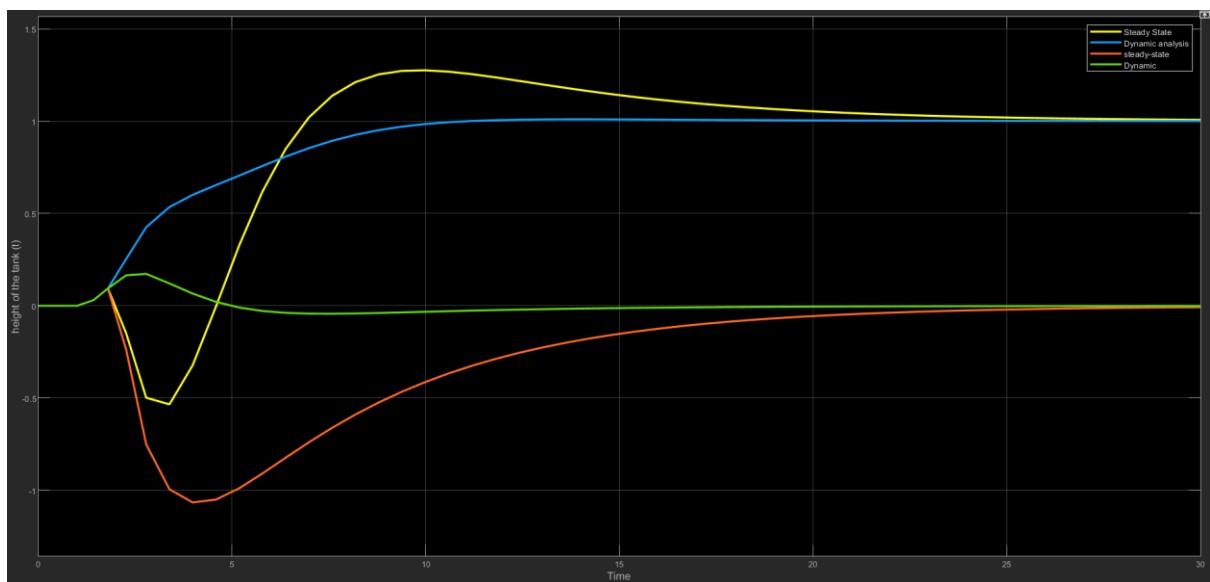
Output D)



Output E)



Mixed



Dynamic shows a better response in both of them