UFU 45 ANOS

Prova 1

Sistemas de Controle

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Novembro 2023

Sumário

Questão 1)

Letra a)

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1) a) $f(t) = 3 + 7t + t^2 + \delta(t)$

$$\mathcal{L}\{f(t)\} = \mathcal{L}\{3 + 7t + t^2 + \delta(t)\} = 3 \cdot \frac{1}{s} + 7 \cdot \frac{1}{s^2} + \frac{2}{s^3} + 1$$

$$\therefore F(s) = \frac{3}{s} + \frac{7}{s^2} + \frac{2}{s^3} + 1 = \frac{s^3 + 3s^2 + 7s + 2}{s^3}$$

Letra b)

b) $f(t) = t\cos 3t = -(-t)\cos 3t$

$$\mathcal{L}\{f(t)\} = \mathcal{L}\{-(-t)\cos 3t\} = -\frac{d}{ds}\left(\frac{s}{s^2+9}\right) = -\left(\frac{(s^2+9) - s \cdot 2s}{(s^2+3^2)^2}\right)$$

$$\therefore F(s) = \frac{s^2 - 9}{(s^2+9)^2}$$

Letra c)

c) $$F(s) = \frac{1}{s(s+2)^2} = \frac{A}{s} + \frac{B}{s+2} + \frac{C}{(s+2)^2} = \frac{A(s+2)^2 + Bs(s+2) + Cs}{s(s+2)^2}$$

$1 = A(s+2)^2 + Bs(s+2) + Cs$

- $s \to 0$: $1 = 4A \Rightarrow A = 1/4$
- $s \to -2$: $1 = -2C \Rightarrow C = -1/2$
- $s \to -1$: $1 = A - B - C \Rightarrow 1/4 - B + 1/2 = 1 \Rightarrow B = -1/4$

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

$$\mathcal{L}^{-1}\{F(s)\} = \frac{1}{4} \cdot 1 - \frac{1}{4} \cdot e^{-2t} - \frac{1}{2} \cdot e^{-2t} \cdot t$$

$$\therefore f(t) = \frac{e^{-2t}}{4} \cdot (-2t + e^{2t} - 1)$$

Letra d)

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$$d)\ F(s) = \frac{3s+2}{s(s+1)(s^2+4s+10)} = \frac{A}{s} + \frac{B}{s+1} + \frac{Cs+D}{s^2+4s+10}$$

$$3s+2 = A(s+1)(s^2+4s+10) + Bs(s^2+4s+10) + s(Cs+D)(s+1)$$

- $s \to 0 : A = 1/5$
- $s \to -1 : B = 1/7$

$$\therefore 3s+2 = \frac{1}{5}(s+1)(s^2+4s+10) + \frac{1}{7}s(s^2+4s+10) + (Cs+D)s(s+1)$$

$$\Rightarrow 3s+2 = s^3\left(C+\frac{12}{35}\right) + s^2\left(D+C+\frac{11}{7}\right) + s\left(D+\frac{148}{35}\right) + 2$$

$$\begin{cases} D + 148/35 = 3 \\ D + C + 11/7 = 0 \\ C + 12/35 = 0 \end{cases} \xrightarrow[\text{o sistema}]{\text{Resolvendo}} C = -12/35 \ ; \ D = -43/35$$

$$\therefore F(s) = \frac{1/5}{s} + \frac{1/7}{s+1} + \frac{(-12/35)s - 43/35}{s^2+4s+10} = \frac{1}{5s} + \frac{1}{7(s+1)} + \frac{-12s-43}{35(s^2+4s+10)}$$

$$= \frac{1}{5s} + \frac{1}{7(s+1)} - \frac{12}{35}\left(\frac{s+2}{(s+2)^2+6}\right) - \frac{19}{35}\left(\frac{1}{(s+2)^2+6}\right)$$

$$\therefore \mathcal{L}^{-1}\{F(s)\} = \mathcal{L}^{-1}\left\{\frac{1}{5s}\right\} + \mathcal{L}^{-1}\left\{\frac{1}{7(s+1)}\right\} - \frac{12}{35}\mathcal{L}^{-1}\left\{\frac{s+2}{(s+2)^2+6}\right\} - \frac{19}{35}\mathcal{L}^{-1}\left\{\frac{1}{(s+2)^2+6}\right\}$$

$$\therefore f(t) = \frac{1}{5} + \frac{1}{7}e^{-t} - \frac{12}{35}e^{-2t}\cos(\sqrt{6}\cdot t) - \frac{19}{35}e^{-2t}\frac{1}{\sqrt{6}}\,\mathrm{sen}(\sqrt{6}\cdot t)$$

$$f(t) = \frac{1}{210}\cdot e^{-2t}\left(30e^{t} + 42e^{2t} - 19\sqrt{6}\,\mathrm{sen}(\sqrt{6}\cdot t) - 72\cos(\sqrt{6}\cdot t)\right)$$

Questão 2)

Letra a)

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2) a) O sistema possui três graus de liberdade. Para M_1, temos:

$$\begin{bmatrix}\text{Soma das impedâncias} \\ \text{conectadas ao movimento} \\ \text{em } X_1\end{bmatrix} X_1(s) - \begin{bmatrix}\text{Soma das impedâncias} \\ \text{entre } X_1 \text{ e } X_2\end{bmatrix} X_2(s)$$

$$- \begin{bmatrix}\text{Soma das impedâncias} \\ \text{entre } X_1 \text{ e } X_3\end{bmatrix} X_3(s) = \begin{bmatrix}\text{Soma das forças} \\ \text{aplicadas em } X_1\end{bmatrix}$$

Segue-se analogamente para M_2 e M_3 e nos próximos exercícios.

Logo, tem-se:

M_1:

$$[M_1 . s^2 + D_1 s + K_1] X_1(s) - [D_1 s] X_2(s) - [0] X_3(s) = 0$$

$$\Rightarrow (4s^2 + 2s + 6) X_1(s) - 2s X_2(s) = 0 \quad (I)$$

M_2:

$$[M_2 s^2 + (D_1 + D_2) s + K_2] X_2(s) - [D_1 s] X_1(s) - [K_2] X_3(s) = F(s)$$

$$\Rightarrow (4s^2 + 4s + 6) X_2(s) - 2s X_1(s) - 6 X_3(s) = F(s) \quad (II)$$

M_3:

$$[M_3 s^2 + D_3 s + K_2] X_3(s) - [K_2] X_2(s) - [0] X_1(s) = 0$$

$$\Rightarrow (4s^2 + 2s + 6) X_3(s) - 6 X_2(s) = 0 \quad (III)$$

Em (I):

$$X_2(s) = \frac{4s^2 + 2s + 6}{2s} X_1(s) \quad (IV)$$

Em (III):

$$X_2(s) = \frac{(4s^2 + 2s + 6) X_3(s)}{6} \quad (V)$$

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Por (IV) e (V), igualando:

$$\frac{(4s^2+2s+6)X_1(s)}{2s} = \frac{(4s^2+2s+6)X_3(s)}{6}$$

$X_3(s) = \frac{6X_1(s)}{2s}$ (VI) e analogamente: $X_1(s) = \frac{2s\,X_3(s)}{6}$ (VII)

Finalmente, substituindo (IV) e (VI) em (II):

$$(4s^2+4s+6).\frac{(4s^2+2s+6).X_1(s)}{2s} - 2s\,X_1(s) - 6.\frac{6X_1(s)}{2s} = F(s)$$

$$X_1(s)\left(\frac{(4s^2+4s+6)\cdot(4s^2+2s+6)}{2s} - 2s - \frac{36}{2s}\right) = F(s) \Rightarrow X_1(s).(8s^3+12s^2+26s+18) = F(s)$$

$$\therefore \frac{X_1(s)}{F(s)} = \frac{1}{8s^3+12s^2+26s+18}$$

A partir de (VII), tem-se:

$$\frac{2s.X_3(s)}{6F(s)} = \frac{1}{8s^3+12s^2+26s+18}$$

$$\therefore \frac{X_3(s)}{F(s)} = \frac{6}{2s.(8s^3+12s^2+26s+18)} = \frac{3}{8s^4+12s^3+26s^2+18s}$$

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Letra b)

2) b) A partir dos passos descritos no item a), temos as equações de movimento:

Em θ_1:

$$[Js^2 + Ds + K]\theta_1(s) - [Ds + K]\theta_2(s) = 0$$

$$\Rightarrow (5s^2 + 9s + 9)\theta_1(s) - (s+9)\theta_2(s) = 0 \quad (\mathrm{I})$$

Em θ_2:

$$(3s^2 + s + 12)\theta_2(s) - (s+9)\theta_1(s) = T(s) \quad (\mathrm{II})$$

Isolando em (I):

$$\theta_2(s) = \frac{(5s^2 + 9s + 9)\theta_1(s)}{s+9} \quad \text{Analogamente: } \theta_1(s) = \frac{(s+9)\theta_2(s)}{5s^2 + 9s + 9} \quad (\mathrm{III})$$

Substituindo em (II)

$$\frac{(3s^2 + s + 12).(5s^2 + 9s + 9)\theta_1(s)}{s+9} - (s+9)\theta_1(s) = T(s)$$

$$\theta_1(s)\left(\frac{(3s^2 + s + 12)(5s^2 + 9s + 9)}{s+9} - (s+9)\right) = T(s) = \theta_1(s).\left(\frac{15s^4 + 32s^3 + 95s^2 + 99s + 27}{s+9}\right)$$

$$\therefore \frac{\theta_1(s)}{T(s)} = \frac{s+9}{15s^4 + 32s^3 + 95s^2 + 99s + 27}$$

Com (III), tem-se:

$$\frac{(s+9)\theta_2(s)}{(5s^2 + 9s + 9)T(s)} = \frac{s+9}{15s^4 + 32s^3 + 95s^2 + 99s + 27} \Rightarrow \frac{\theta_2(s)}{T(s)} = \frac{5s^2 + 9s + 9}{15s^4 + 32s^3 + 95s^2 + 99s + 27}$$

Letra c)

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2) c) Refletindo as impedâncias para θ_2:

$$\theta_2(s)\left\{[J_e]s^2 + [D_e]s + [K_e]\right\} = F(s)$$

$$\theta_2(s)\left\{\left[150 + 3.\left(\frac{50}{5}\right)^2 + 100.\left(\frac{5}{25}\cdot\frac{50}{5}\right)^2\right]s^2 + \left[500.\left(\frac{5}{25}\cdot\frac{50}{5}\right)^2\right]s + \left[300 + 3.\left(\frac{50}{5}\right)^2\right]\right\}$$
$$= \left(\frac{50}{5}\right)T(s)$$

Portanto:

$$\theta_2(s).\left[850s^2 + 2000s + 600\right] = \left(\frac{50}{5}\right)T(s)$$

$$\therefore \frac{\theta_2(s)}{T(s)} = \frac{1}{85s^2 + 200s + 60}$$

Questão 3)

Letra a)

$$3)\ a)\ \frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s)H(s)} = \frac{\frac{\omega_n^2}{s(s+2\zeta\omega_n)}}{1 + \frac{\omega_n^2}{s(s+2\zeta\omega_n)}} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Assim, sabendo que $\zeta = 0{,}8$ e $\omega_n = 25$ rad/s, os parâmetros de desempenho são:

$$\omega_d = \omega_n\sqrt{1-\zeta^2} = 25\sqrt{1-0{,}8^2} = \underline{15 \text{ rad/s}}$$

$$\sigma_d = \zeta\omega_n = 0{,}8 . 25 = \underline{20}$$

$$T_r \cong \frac{1{,}8}{\omega_n} = \frac{1{,}8}{25} = \underline{0{,}072 s}$$

$$T_p = \frac{\pi}{\omega_d} = \frac{\pi}{20} = \underline{0{,}157 s}$$

$$T_s = \frac{4}{\zeta\omega_n} = \frac{4}{\sigma_d} = \frac{4}{20} = \underline{0{,}2 s}$$

$$M_p = e^{-\left(\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right)} . 100\% = e^{-\left(\frac{0{,}8\pi}{\sqrt{0{,}36}}\right)} . 100\% = \underline{1{,}516\%}$$

$$\theta = \cos^{-1}(\zeta) = \cos^{-1}(0{,}8) \cong \underline{36{,}87°}$$

Letra b)

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3) b) $\sum F = m.a(t)$

$F(s) - f_v . sX(s) - KX(s) = m . s^2 . X(s)$

$F(s) = m . s^2 X(s) + f_v . s . X(s) + KX(s) \Rightarrow \frac{F(s)}{m} = X(s)\left[s^2 + \frac{f_v}{m} . s + \frac{K}{m}\right]$

$\frac{X(s)}{F(s)} = \frac{1/m}{s^2 + f_v/m \cdot s + K/m} \Rightarrow \frac{X(s)}{F(s)} = \frac{0{,}2}{s^2 + 0{,}4s + 4}$

Com isso, os parâmetros de desempenho são:

$\omega_n^2 = 4 \Rightarrow \omega_n = \sqrt{4} = \underline{2 \text{ rad/s}}$

$2 . \zeta . \omega_n = 0{,}4 \Rightarrow \zeta = \frac{0{,}4}{4} = \underline{0{,}1}$

$\sigma d = \zeta \omega_n = 0{,}1 . 2 = \underline{0{,}2}$

$\omega_d = \omega_n \sqrt{1 - \zeta^2} = 2 . \sqrt{0{,}99} = \underline{1{,}989 \text{ rad/s}}$

$T_r \cong \frac{1{,}8}{\omega_n} = \frac{1{,}8}{2} = \underline{0{,}9 s}$

$T_p = \frac{\pi}{\omega_d} = \frac{\pi}{1{,}989} = \underline{1{,}579 s}$

$T_s = \frac{4}{\sigma d} = \frac{4}{0{,}2} = \underline{20 s}$

$M_p = e^{-\left(\frac{\pi \zeta}{\sqrt{1 - \zeta^2}}\right)} . 100\% = e^{-\left(\frac{\pi . 0{,}1}{\sqrt{0{,}99}}\right)} . 100\% = \underline{72{,}92\%}$

$\theta = \cos^{-1} \zeta = \cos^{-1} 0{,}1 \cong \underline{84{,}26°}$

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Letra c)

3) c) Em J, considerando $\theta_1(s) = \theta_2(s)$, tem-se:

$$T(s) - Js^2\theta_1(s) - Ds\,\theta_1(s) - K\theta_1(s) = 0$$

Substituindo valores:

$$\frac{T(s)}{2} = \theta_1(s)\left[s^2 + 1/2 \cdot s + 1/2\right] \Rightarrow \frac{\theta_1(s)}{T(s)} = \frac{\theta_2(s)}{T(s)} = \frac{1/2}{s^2 + \frac{1}{2}s + \frac{1}{2}}$$

Dessa forma, os parâmetros de desempenho serão:

$$\omega_n^2 = 1/2 \Rightarrow \omega_n = \underline{0{,}707 \text{ rad/s}}$$

$$2.\zeta.\omega_n = 1/2 \Rightarrow \zeta = \frac{1}{2}.\frac{1}{2.0{,}707} = \underline{0{,}354}$$

$$\sigma_d = \zeta\omega_n = 0{,}354.0{,}707 = \underline{0{,}251}$$

$$\omega_d = \omega_n\sqrt{1-\zeta^2} = 0{,}707\sqrt{1-0{,}354^2} = \underline{0{,}661 \text{ rad/s}}$$

$$T_r \doteq \frac{1{,}8}{\omega_n} = \frac{1{,}8}{0{,}707} = \underline{2{,}546\,s}$$

$$T_p = \frac{\pi}{\omega_d} = \frac{\pi}{0{,}661} = \underline{4{,}753\,s}$$

$$T_s = \frac{4}{\sigma_d} = \frac{4}{0{,}25} = \underline{16\,s}$$

$$M_p = e^{-\left(\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right)}.100\% = e^{-\left(\frac{0{,}354\pi}{\sqrt{0{,}935}}\right)}.100\% = \underline{30{,}993\%}$$

$$\theta = \cos^{-1}\zeta = \cos^{-1}0{,}354 = \underline{69{,}3°}$$

Questão 4)

Letra a)

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4) a) $H(s) = \dfrac{G(s)}{1+G(s)H(s)} = \dfrac{\dfrac{450}{s^4+3s^3+10s^2+30s+150}}{1+\dfrac{450}{s^5+3s^4+10s^3+30s^2+150s}} = \dfrac{450s}{s^5+3s^4+10s^3+30s^2+150s+450}$

Encontrando os polos:

$s^5+3s^4+10s^3+30s^2+150s+450=0 \Rightarrow (s+3)(s^4+10s^2+150)=0$

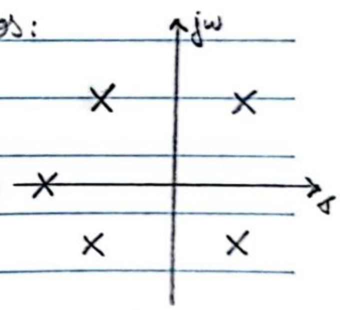
- $(s+3)=0 \Rightarrow \underline{s_0=-3}$
- $s^4+10s^2+150=0 \Rightarrow s^2=x \Rightarrow x^2+10x+150=0$

$\Delta = 10^2-4.1.150=-500$

$x = \dfrac{-10\pm\sqrt{-500}}{2} = \dfrac{-10\pm j.10\sqrt{5}}{2} = -5\pm j5\sqrt{5}$

$s^2=x \Rightarrow s=\pm\sqrt{x} \Rightarrow \underline{s=\pm\sqrt{-5\pm j5\sqrt{5}}}$

Polos:



Dessa forma, são 3 polos presentes nos reais negativos $(-3;\ -\sqrt{-5+j5\sqrt{5}};\ -\sqrt{-5-j5\sqrt{5}})$ e 2 polos nos reais positivos $(\sqrt{-5+j5\sqrt{5}}$ e $\sqrt{-5-j5\sqrt{5}})$. Portanto, o sistema é instável por causa de seus polos com parte real positiva

Letra b)

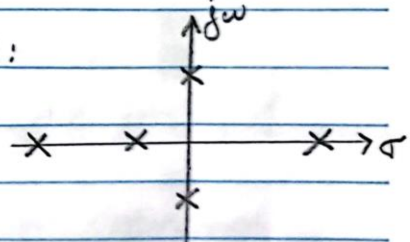
4)b) $H(s) = \dfrac{G(s)}{1-G(s)H(s)} = \dfrac{\dfrac{18}{s^5+s^4-7s^3-7s^2-18s}}{1-\dfrac{18}{s^5+s^4-7s^3-7s^2-18s}} = \dfrac{18}{s^5+s^4-7s^3-7s^2-18s-18}$

Encontrando os polos:

$s^5+s^4-7s^3-7s^2-18s-18=0 \Rightarrow (s+1)(s^2+2)(s-3)(s+3)$

- $s+1=0 \Rightarrow \underline{s=-1}$
- $s^2+2=0 \Rightarrow s=\pm\sqrt{-2} \Rightarrow \underline{s=\pm j\sqrt{2}}$
- $s-3=0 \Rightarrow \underline{s=3}$
- $s+3=0 \Rightarrow \underline{s=-3}$

Polos:



Devido ao polo $s=3$, por estar no semi-plano dos reais positivos, o sistema é dito instável

Questão 5)

Letra a)

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5) a) $T_s = 4s$; $T_p = 1s$; $f_v = 1,5$

- Modelando o sistema:

$$\sum F(t) = m \cdot a(t)$$

$$f(t) - f_v \dot{x}(t) - Kx(t) = m \cdot \ddot{x}(t)$$

$$\ddot{x}(t) + \frac{f_v}{m} \cdot \dot{x}(t) + \frac{K}{m} x(t) = f(t) \cdot \frac{1}{m}$$

$$s^2 X(s) + \frac{f_v}{m} \cdot s X(s) + \frac{K}{m} X(s) = \frac{F(s)}{m}$$

$$X(s)\left[s^2 + \frac{f_v}{m} s + \frac{K}{m}\right] = \frac{F(s)}{m}$$

$$\therefore \frac{X(s)}{F(s)} = \frac{1/m}{s^2 + \frac{f_v}{m} s + \frac{K}{m}}$$

- $T_p = \frac{\pi}{\omega_d} \Rightarrow \omega_d = \frac{\pi}{T_p} \Rightarrow \underline{\omega_d = \pi}$

- $T_s \cong \frac{4}{\sigma_d} \Rightarrow \sigma_d \cong \frac{4}{T_s} \Rightarrow \underline{\sigma_d \cong 1}$

- $\sigma_d = \frac{f_v}{2m} = \frac{1,5}{2m} = \frac{0,75}{m} \Rightarrow m = \frac{0,75}{\sigma_d} = \underline{0,75 \text{ Kg}}$

- $\sigma_d = \zeta \omega_n = \frac{f_v}{2m} \Rightarrow \zeta \omega_n = \frac{1,5}{2 \cdot 0,75} \Rightarrow \zeta = \frac{1}{\omega_n}$

- $\omega_d = \omega_n \sqrt{1 - \zeta^2} \Rightarrow \pi = \omega_n \sqrt{1 - \left(\frac{1}{\omega_n}\right)^2} \Rightarrow \underline{\omega_n = \sqrt{1 + \pi^2}}$

- $\zeta = \frac{1}{\omega_n} = \frac{1}{\sqrt{1+\pi^2}} \cong \underline{0,303}$

- $\theta = \cos^{-1} \zeta = \cos^{-1} 0,303 = \underline{72,36°}$

- $T_r \cong \frac{1,8}{\omega_n} = \frac{1,8}{\sqrt{1+\pi^2}} = \underline{0,545 s}$

- $\omega_n^2 = \frac{K}{m} \Rightarrow \omega_n^2 m = K \Rightarrow K = 8,1522$

- $M_p = e^{-\left(\frac{\pi \zeta}{\sqrt{1-\zeta^2}}\right)} \cdot 100\% = e^{-\left(\frac{\pi \cdot 0,303}{\sqrt{0,908}}\right)} \cdot 100\% = \underline{36,83\%}$

Respostas:

$\omega_d = \pi$

$\sigma_d = 1$

$m = 0,75 \text{ Kg}$

$\omega_n = \sqrt{1 + \pi^2} \cong 3,29 \text{ rad/s}$

$\theta = 72,36°$

$\zeta = 0,303$

$T_r = 0,545 s$

$K = 8,1522 \text{ N/m}$

$M_p = 36,83\%$

$T_p = 1s$

$T_s = 4s$

Letra b)

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5) b)

A modelagem será feita a partir da função:

$$\frac{X(s)}{F(s)} = \frac{1/0,75}{s^2+2s+10,8696}$$

, em Python, fazendo uso das bibliotecas: numpy, matplotlib e scipy.

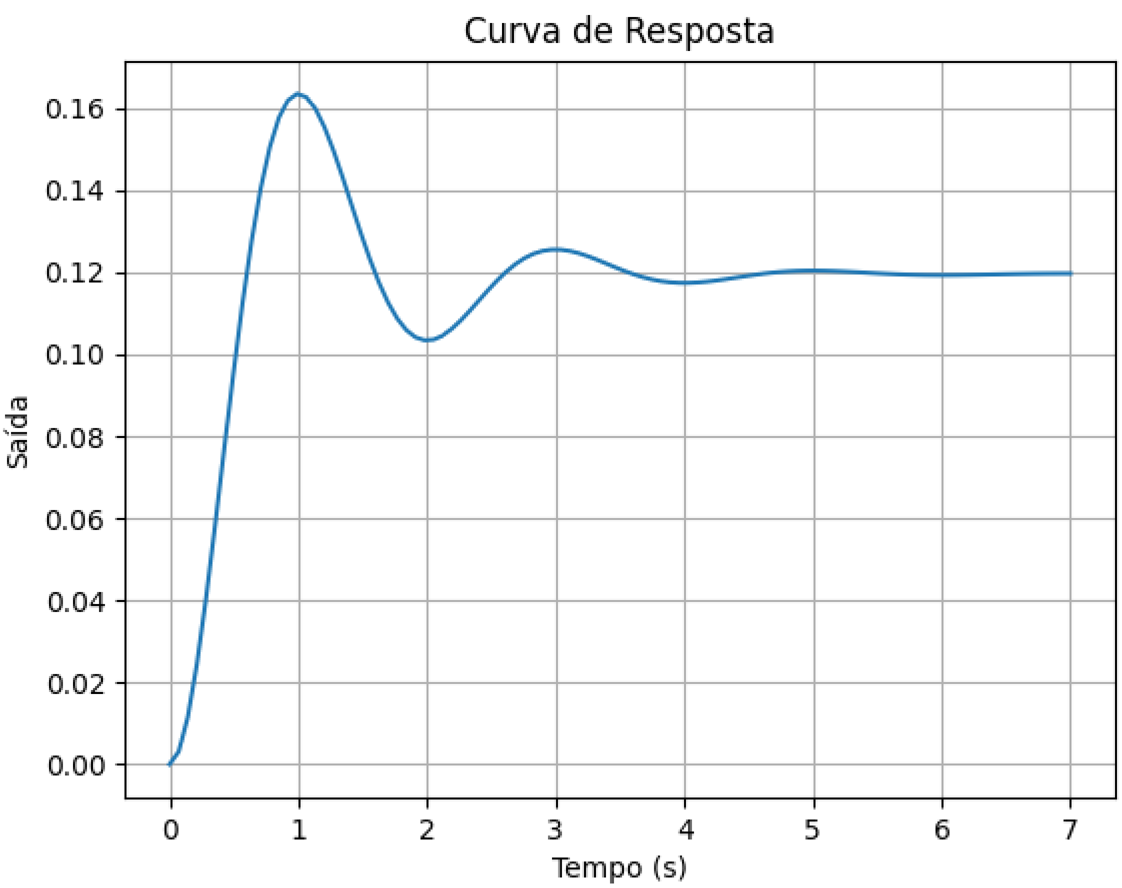
Código:

```python
import numpy as np
import matplotlib.pyplot as plt
from scipy import signal

#Função de Transferência
num = [1.3]
den = [1, 2, 10.8696]
system = signal.TransferFunction(num,den)

#Função de entrada
t, y = signal.step(system)

#Plotar resposta
plt.plot(t, y)
plt.title('Curva de Resposta')
plt.xlabel('Tempo (s)')
plt.ylabel('Saída')
plt.grid(True)
plt.show()
```



Questão 6)

Letra a)

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6) a) No loop interno, $G_e(s) = \frac{1}{s+12} \cdot \frac{20}{s} = \frac{20}{s(s+12)}$, e $H_e(s) = 0{,}2s$.

Portanto, $T_e(s) = \frac{G_e(s)}{1+G_e(s)H_e(s)} = \frac{20}{s(s+16)}$. Combinando com a função de transferência equivalente do par paralelo, $G_p(s) = 20$, o sistema é reduzido a um sistema de feedback unitário equivalente com $G(s) = G_p(s)T_e(s) = 20 \cdot \frac{20}{s(s+16)} = \frac{400}{s(s+16)}$. Portanto, $T(s) = \frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s)} = \frac{400}{s^2+16s+400}$

Letra b)

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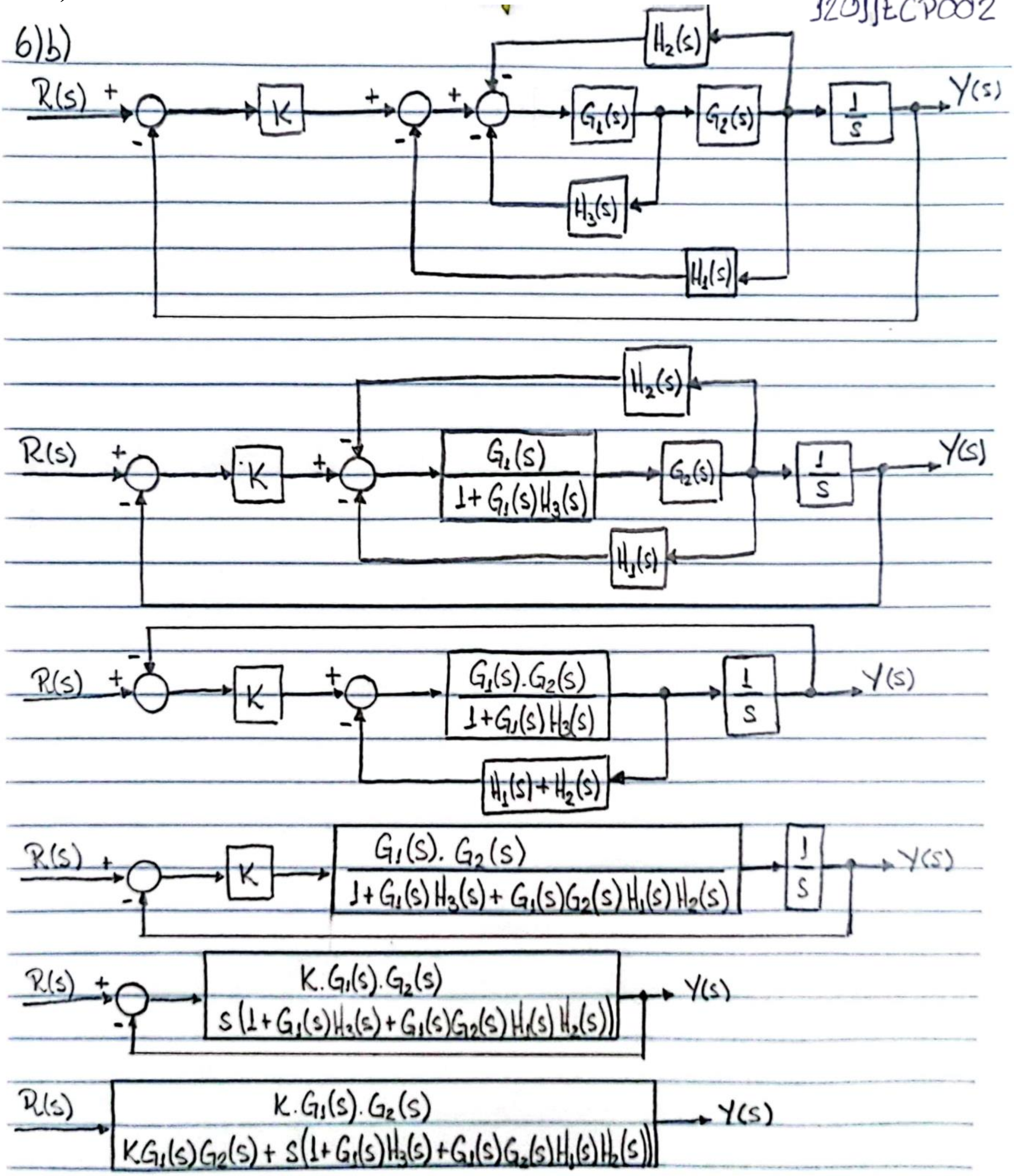
6)b)



Logo, a Função de Transferência $H(s) = \dfrac{Y(s)}{R(s)}$ é dada por:

$$H(s) = \frac{K.\ G_1(s).\ G_2(s)}{KG_1(s)G_2(s) + S(1 + G_1(s)H_3(s) + G_1(s)G_2(s)H_1(s)H_2(s))}$$