

Revisão de Sistema de Controle II: Compensadores - Eduardo Palhares Júnior

3 de agosto de 2015

1 Exercício

$$G(s) = \frac{1}{\pi} \frac{100}{s + 100} G_M(s)$$

$$G_M(s) = \frac{0,05}{s(0,28s + 0,426)} = \frac{0,1174}{s(0,657s + 1)}$$

$$G(s) = \frac{0,0374}{s(0,01s + 1)(0,657s + 1)}$$

$$\begin{cases} M_p = 10\% = 0,1 \\ t_s = 2\% \leqslant 1s \\ e_{ss} = 0,5\% = 0,005 \end{cases}$$

1.1 Ajuste de Ganho

$$K_v = \frac{1}{e_{ss}} = \lim_{s \rightarrow 0} s K_c G_{av}(s) G_{at}(s) G(s)$$

$$\frac{1}{0,005} = \lim_{s \rightarrow 0} s K_c \frac{T_1 s + 1}{\alpha T_1 s + 1} \frac{T_2 s + 1}{\beta T_2 s + 1} \frac{0,0374}{s(0,01s + 1)(0,657s + 1)}$$

$$200 = 0 K_c \frac{T_1 \cdot 0 + 1}{\alpha T_1 \cdot 0 + 1} \frac{T_2 \cdot 0 + 1}{\beta T_2 \cdot 0 + 1} \frac{0,0374}{0(0,01 \cdot 0 + 1)(0,657 \cdot 0 + 1)}$$

$$200 = 0,0374 K_c \Rightarrow \begin{cases} K_c = 5347,59 \\ K_v = 200 \end{cases}$$

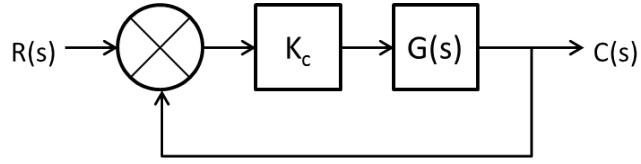


Figura 1: Diagrama de blocos do sistema com ganho ajustado

$$K_c G(s) = \frac{200}{s(0,01s+1)(0,657s+1)}$$

$$\begin{cases} M_{factual} = -4,77^\circ \\ \omega_{cg} = 17,3 \text{ rad/s} \end{cases}$$

1.2 Margem de Fase

$$\xi_{desejada} = \frac{-\ln(M_p)}{\sqrt{\pi^2 + [\ln(M_p)]^2}} = \frac{-\ln(0,1)}{\sqrt{\pi^2 + [\ln(0,1)]^2}} \approx 0,59166$$

$$M_{fdesejada} = \arctan \left(\frac{2\xi}{\sqrt{-2\xi^2 + \sqrt{1 + 4\xi^4}}} \right) = \arctan 1,6378 = 58,5930^\circ$$

1.3 Ângulo de Avanço

$$\phi_m = -180 + M_{fdesejada} + t_{olerância}$$

$$\phi_m = -180^\circ + (-4,77) + 10^\circ = -138^\circ$$

1.4 Fator de Atenuação

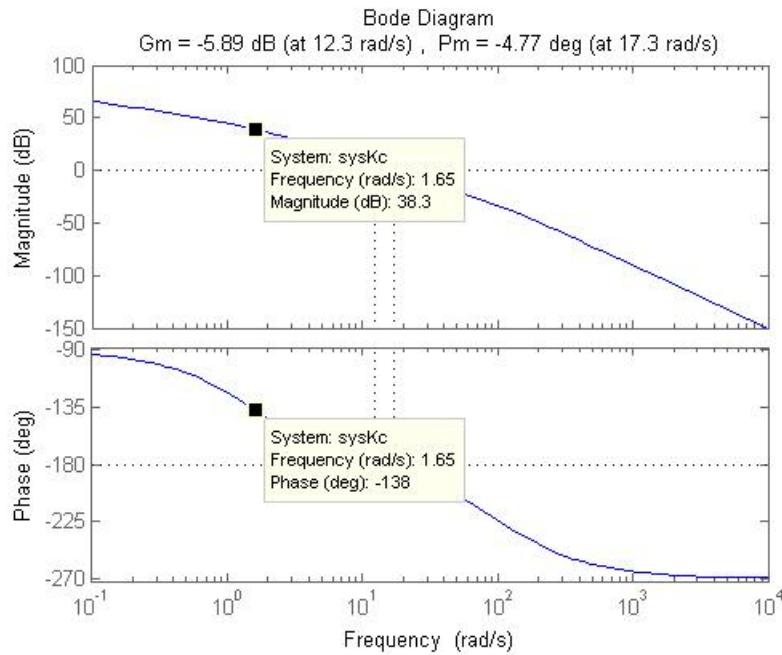


Figura 2: Frequênciа de defasagem m xima

$$\omega_m \approx 1,65 \text{ rad/s}$$

$$|G(s)|_{w=1,65} = 38,3 \text{ dB}$$

$$-20 \log \beta = 38,3 \Rightarrow \beta = 10^{38,3/20} = 82,22$$

1.5 Polos e Zeros do Controlador

$$\omega_m = \frac{10}{T_{at}} \Rightarrow T_{at} = \frac{10}{\omega_m} = 6,061$$

$$\begin{cases} T_{at} = 6,061 \text{ (zero)} \\ \beta T_{at} = 498,3 \text{ (polo)} \end{cases}$$

1.6 Compensador por atraso de fase

$$K_c G_{at}(s) G(s) = K_c \frac{T_{at}s + 1}{\beta T_{at}s + 1} \frac{0,0374}{0(0,010 + 1)(0,6570 + 1)}$$

$$K_c G_{at}(s)G(s) = \frac{6,061s + 1}{498,3s + 1} \frac{200}{s(0,01s + 1)(0,657s + 1)}$$

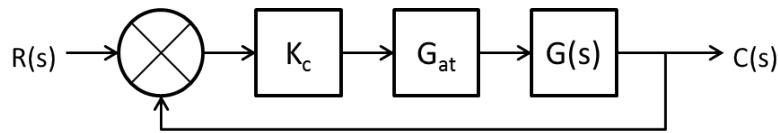


Figura 3: Diagrama de blocos do sistema controlado por atraso de fase

$$K_c G_{av}(s)G(s) = \frac{1212s + 200}{3,274s^4 + 332,4s^3 + 499s^2 + 1}$$

$$\begin{cases} M_{factual} = & 36^\circ \\ \omega_{cg} = & 1,65 \text{ rad/s} \end{cases}$$

1.7 Ângulo de Avanço

$$\phi_m = M_{fdesejada} - M_{atual} + t_{olerância}$$

$$\phi_m = 58,5930^\circ - 36^\circ + 10^\circ = 34,59^\circ$$

1.8 Fator de atenuação

$$\phi_m = \arcsin \frac{1 - \alpha}{1 + \alpha} \Rightarrow \sin \phi_m = \frac{1 - \alpha}{1 + \alpha} \Rightarrow \alpha = \frac{1 - \sin \alpha}{1 + \sin \alpha}$$

$$\alpha = \frac{1 - \sin 34,59}{1 + \sin 34,59} = 0,2757$$

$$-20 \log \left(\frac{1}{\sqrt{\alpha}} \right) = -20 \log \left(\frac{1}{\sqrt{0,2757}} \right) = -5,5953 \text{ dB}$$

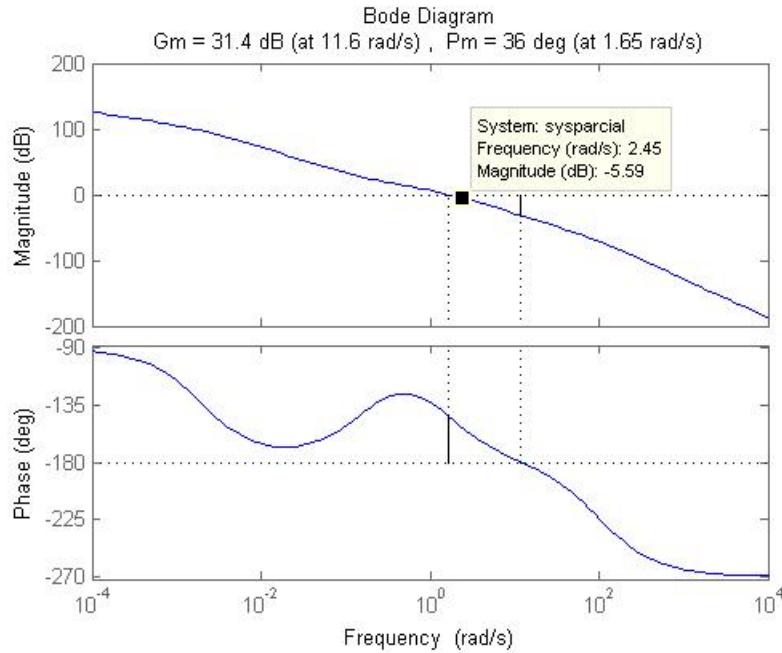


Figura 4: Frequência de defasagem máxima

$$\omega_m \approx 2,45 \text{ rad/s}$$

1.9 Polos e zeros de compensador

$$\omega_m = \frac{1}{\sqrt{\alpha} T_{av}} \Rightarrow T_{av} = \frac{1}{\omega_m \sqrt{\alpha}}$$

$$T_{av} = \frac{1}{2,45\sqrt{0,2757}} \cong 0,7773$$

$$\begin{cases} T_{av} = 0,7773 & (\text{zero}) \\ \alpha T_{av} = 0,2143 & (\text{polo}) \end{cases}$$

1.10 Compensador por atraso-avanço de fase

$$K_c G_{at}(s) G(s) = K_c \frac{T_{at}s + 1}{\beta T_{at}s + 1} \frac{T_{av}s + 1}{\alpha T_{av}s + 1} \frac{0,0374}{0(0,010 + 1)(0,6570 + 1)}$$

$$K_c G_{at}(s) G(s) = \frac{6,061s + 1}{498,3s + 1} \frac{10,7773s + 1}{10,2143s + 1} \frac{200}{s(0,01s + 1)(0,657s + 1)}$$

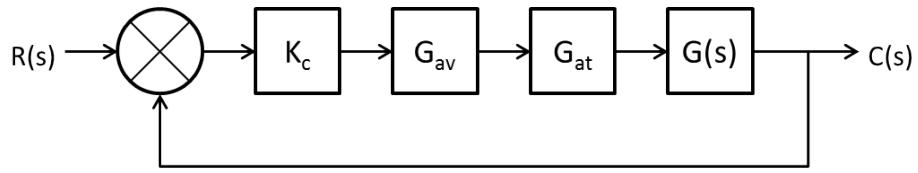


Figura 5: Diagrama de blocos do sistema controlado por atraso-avanço de fase

$$K_c G_{av}(s) G(s) = \frac{642,2s^2 + 1368s + 200}{0,7017s^5 + 47,51s^4 + 439,3s^3 + 499,2s^2 + s}$$

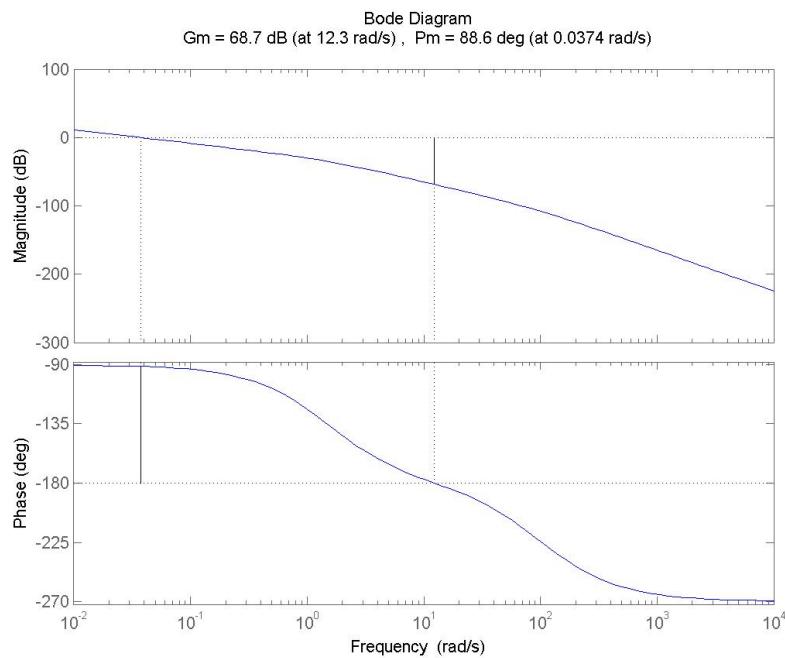


Figura 6: Diagrama de Bode do sistema sem compensação

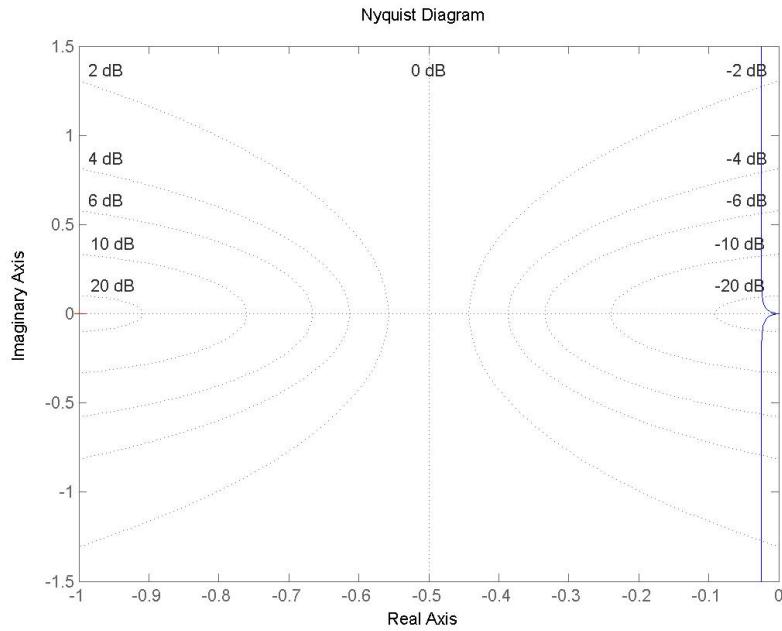


Figura 7: Diagrama de Nyquist do sistema sem compensação

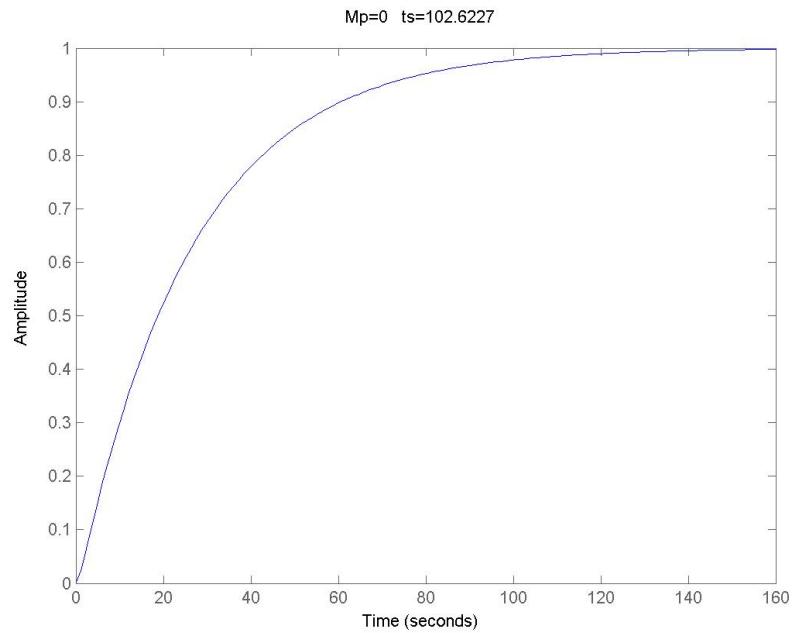


Figura 8: Resposta do sistema ao degrau unitário sem compensação

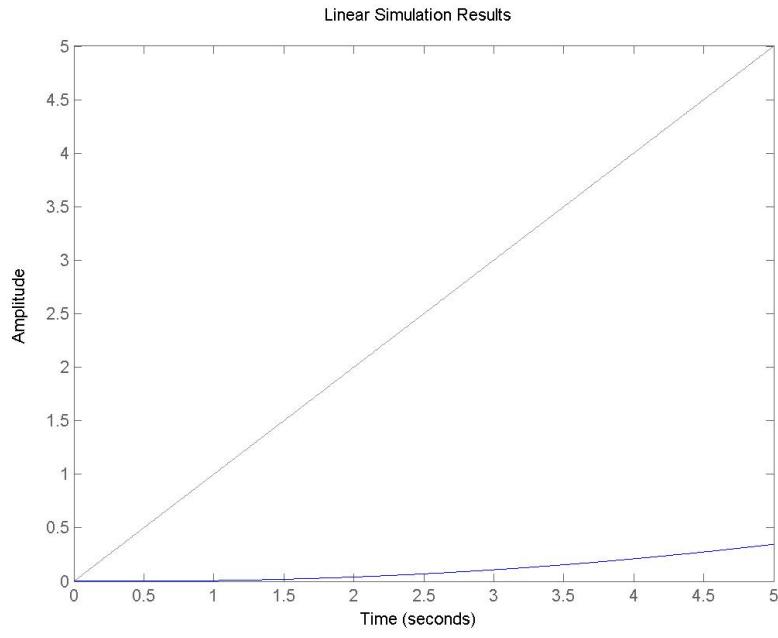


Figura 9: Resposta do sistema a rampa unitária sem compensação

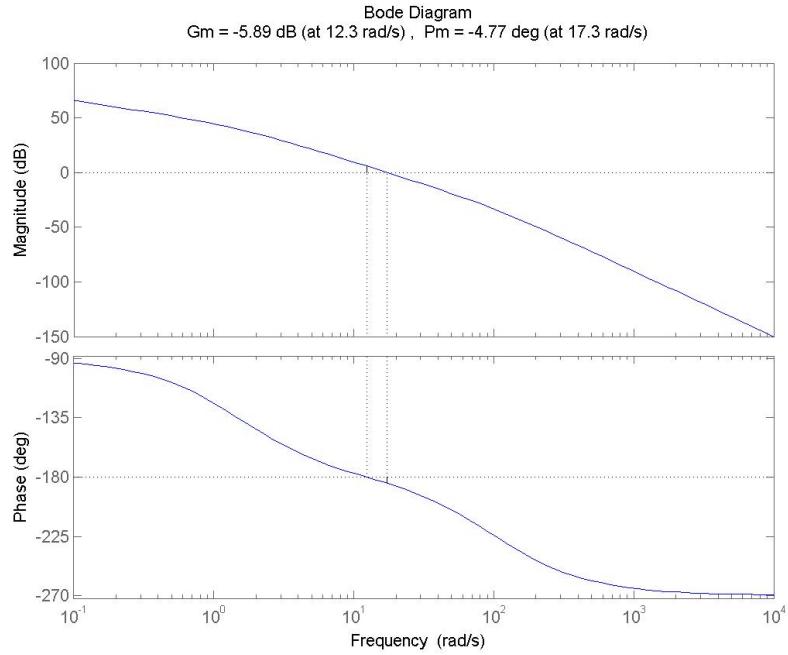


Figura 10: Diagrama de Bode do sistema com ajuste de ganho

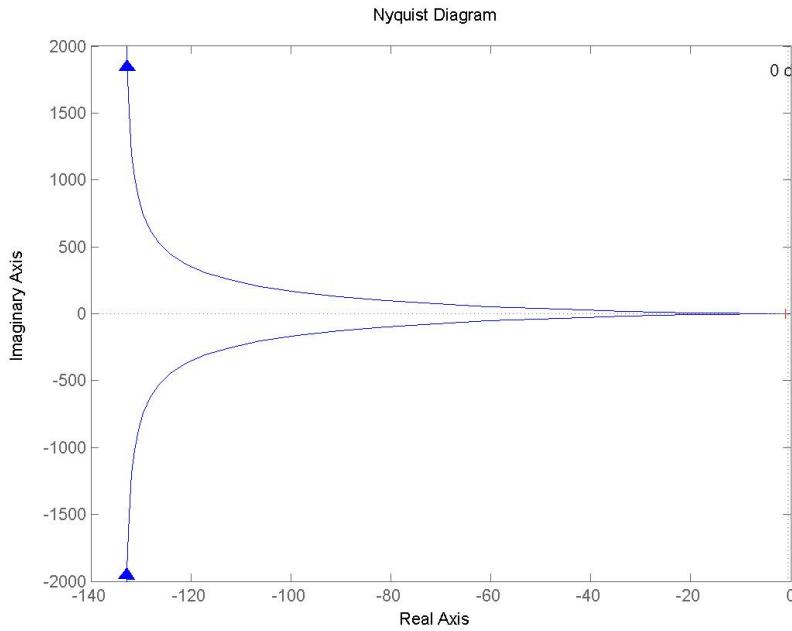


Figura 11: Diagrama de Nyquist do sistema com ajuste de ganho

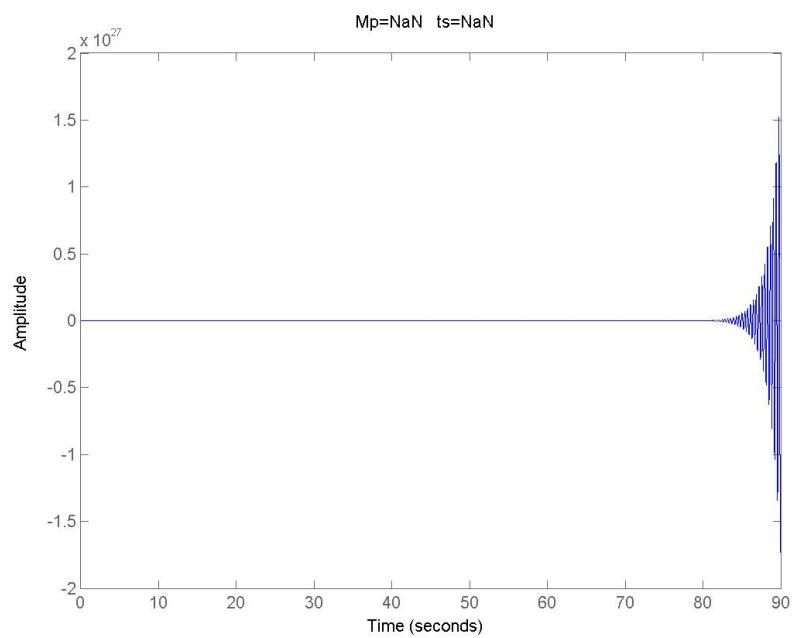


Figura 12: Resposta do sistema ao degrau unitário com ajuste de ganho

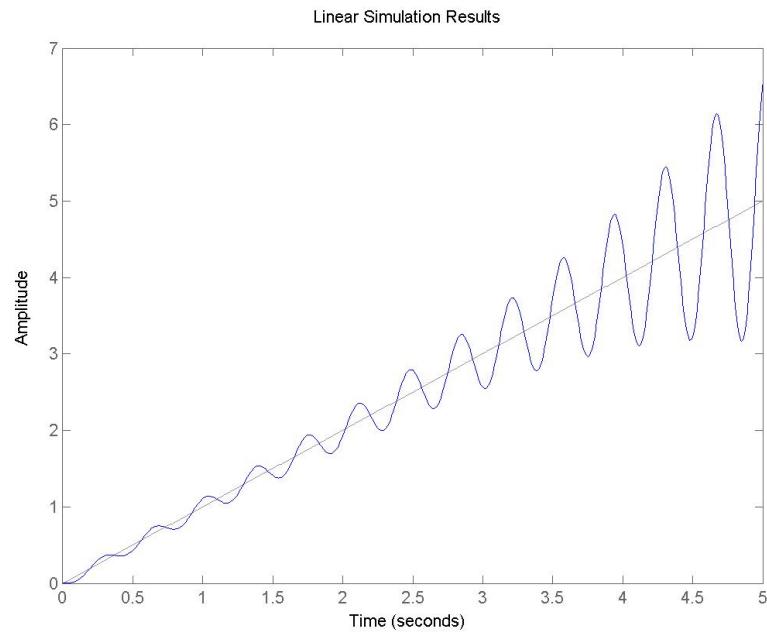


Figura 13: Resposta do sistema a rampa unitária com ajuste de ganho

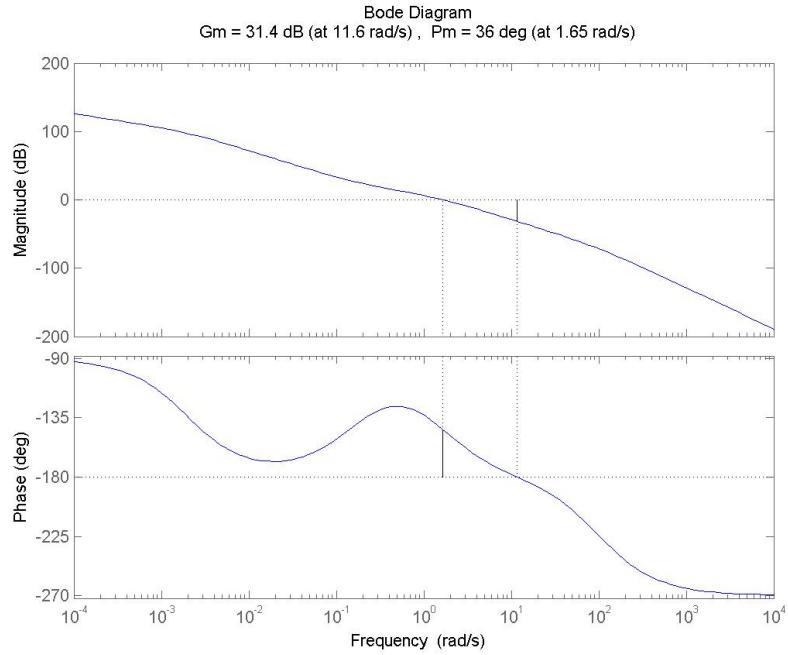


Figura 14: Diagrama de Bode do sistema com atraso de fase

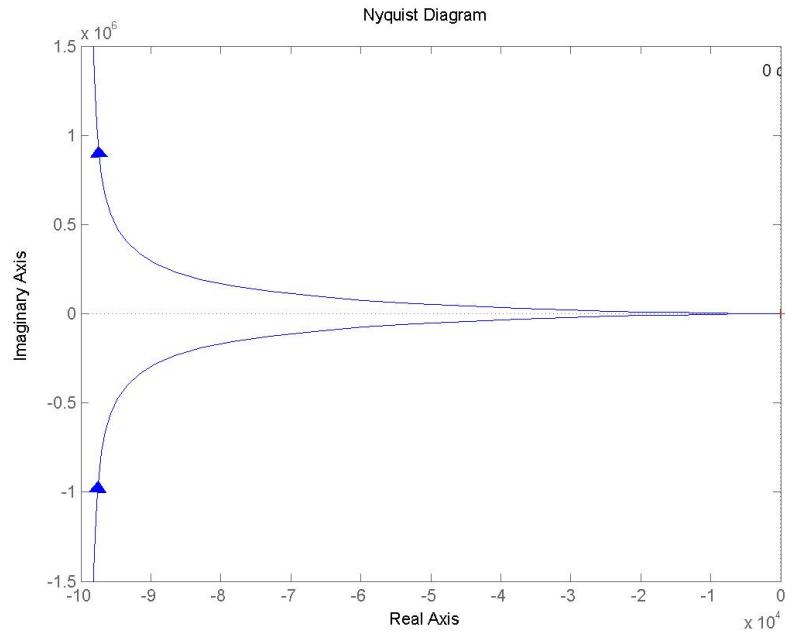


Figura 15: Diagrama de Nyquist do sistema com atraso de fase

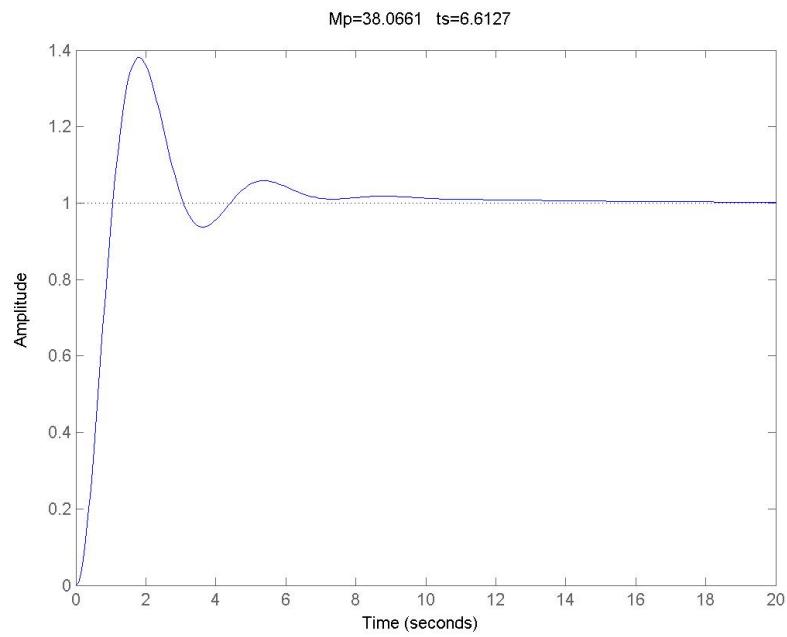


Figura 16: Resposta do sistema ao degrau unitário compensado por atraso

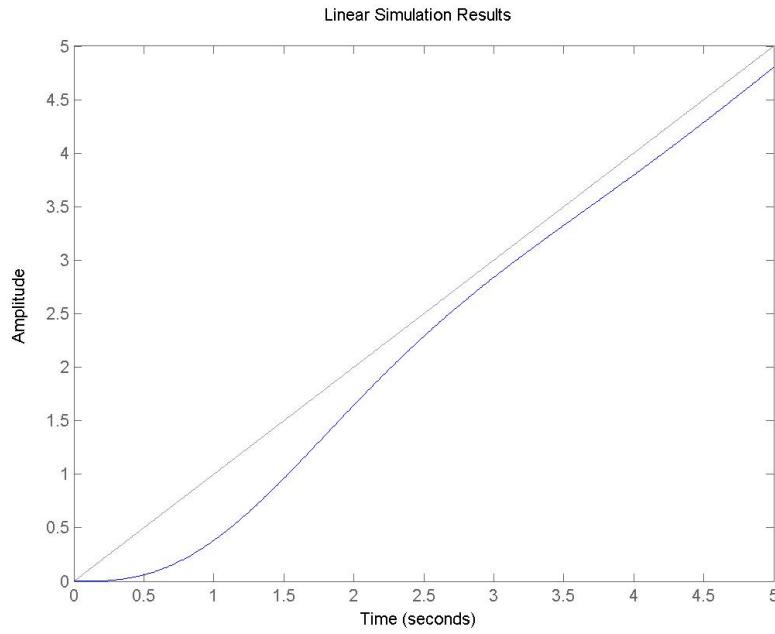


Figura 17: Resposta do sistema a rampa unitária compensado por atraso

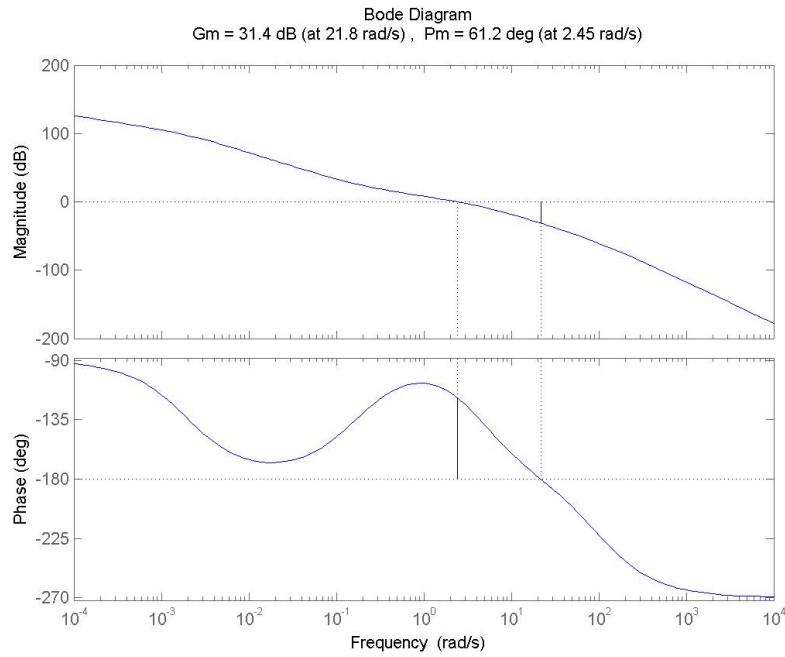


Figura 18: Diagrama de Bode do sistema com atraso-avanço de fase

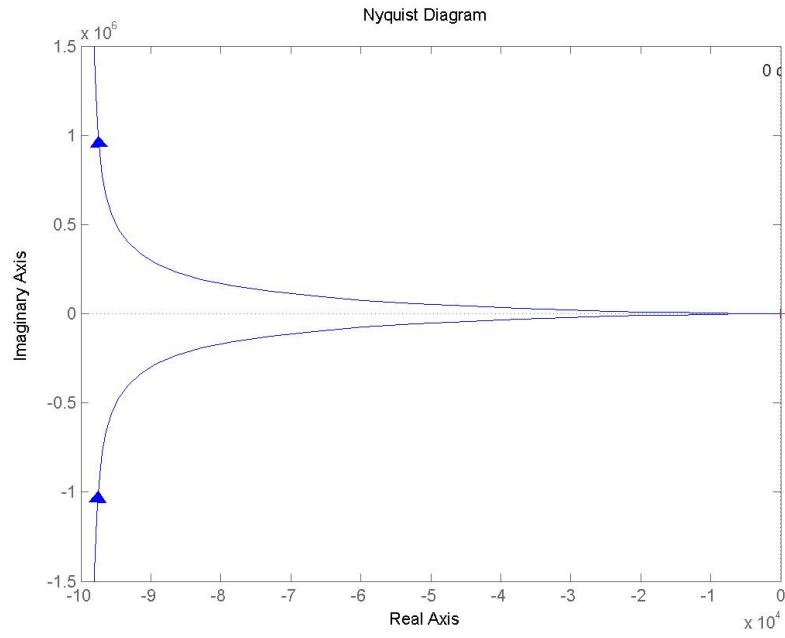


Figura 19: Diagrama de Nyquist do sistema com atraso-avanço de fase

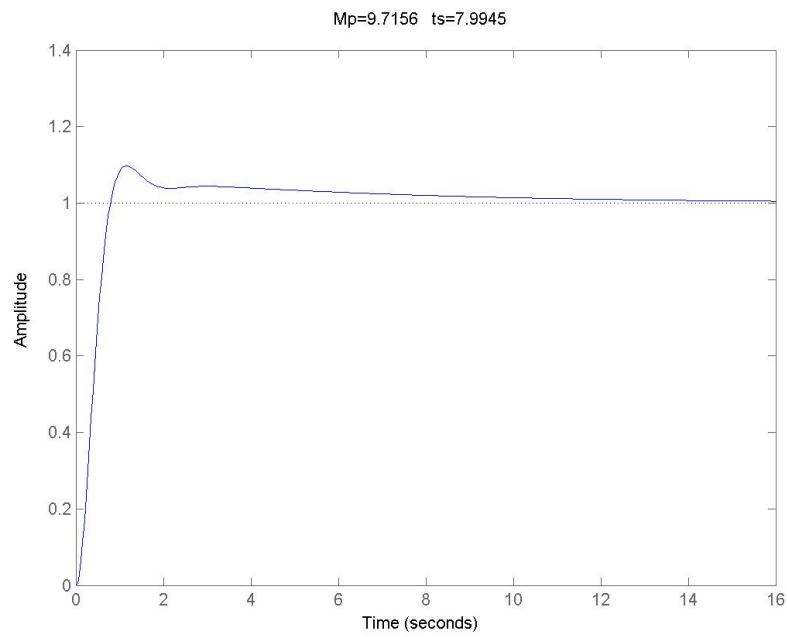


Figura 20: Resposta do sistema ao degrau unitário compensado por atraso-avanço

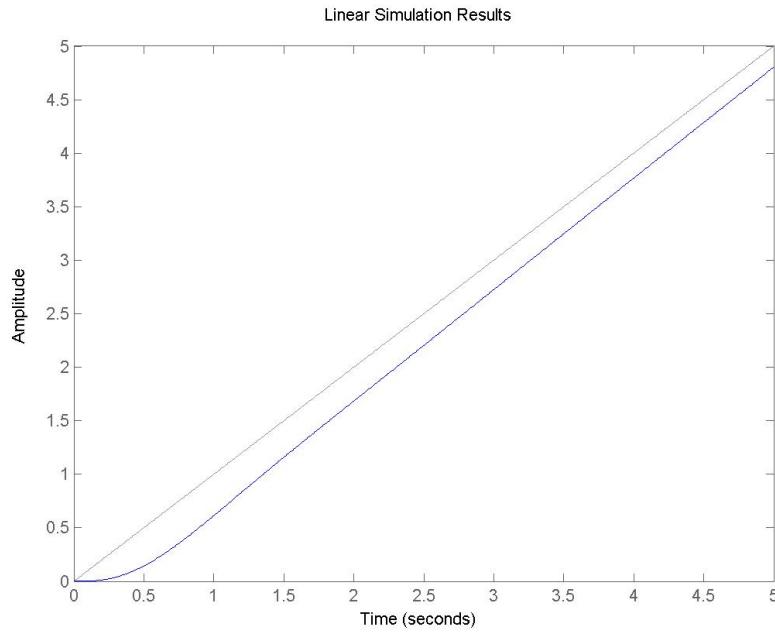


Figura 21: Resposta do sistema a rampa unitária compensado por atraso-avanço

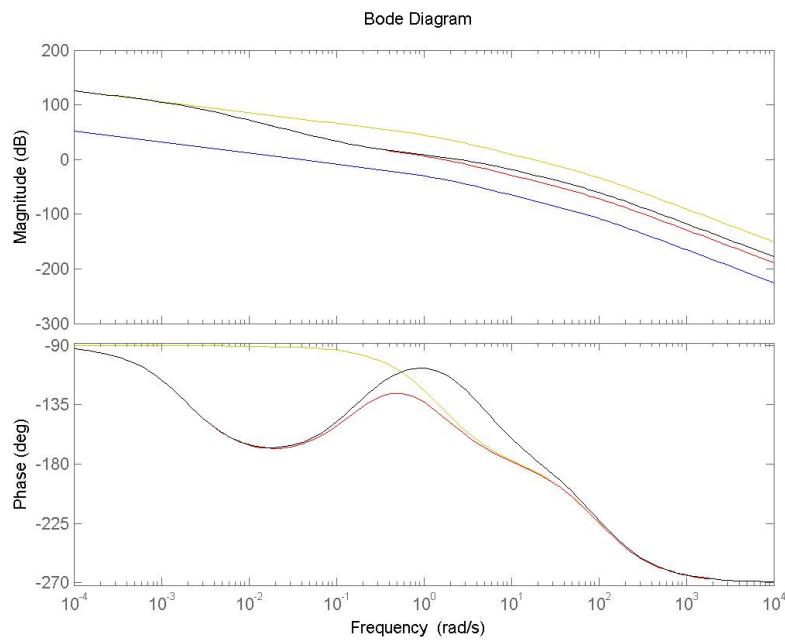


Figura 22: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

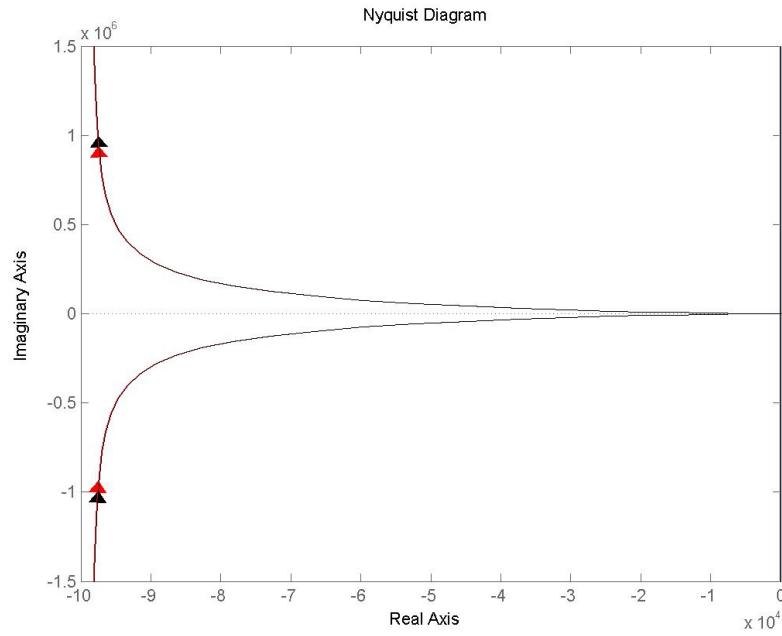


Figura 23: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

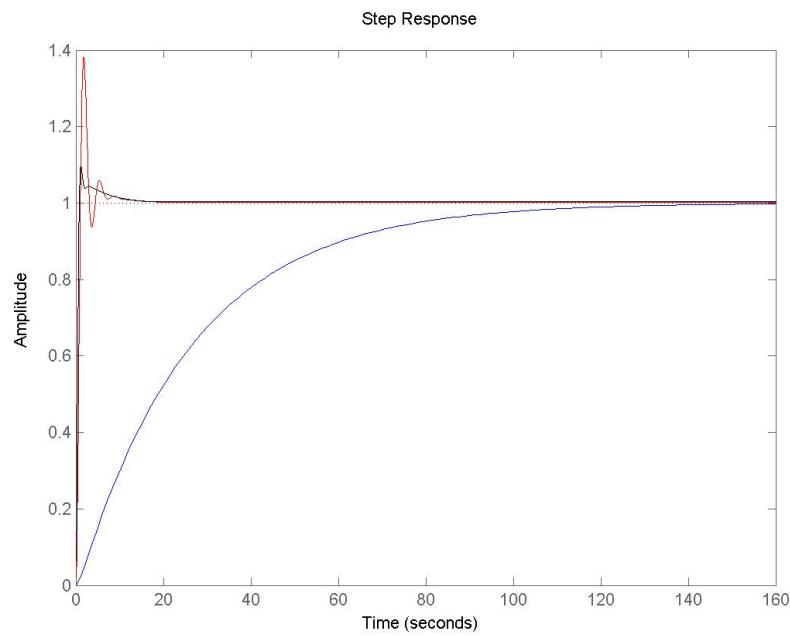


Figura 24: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

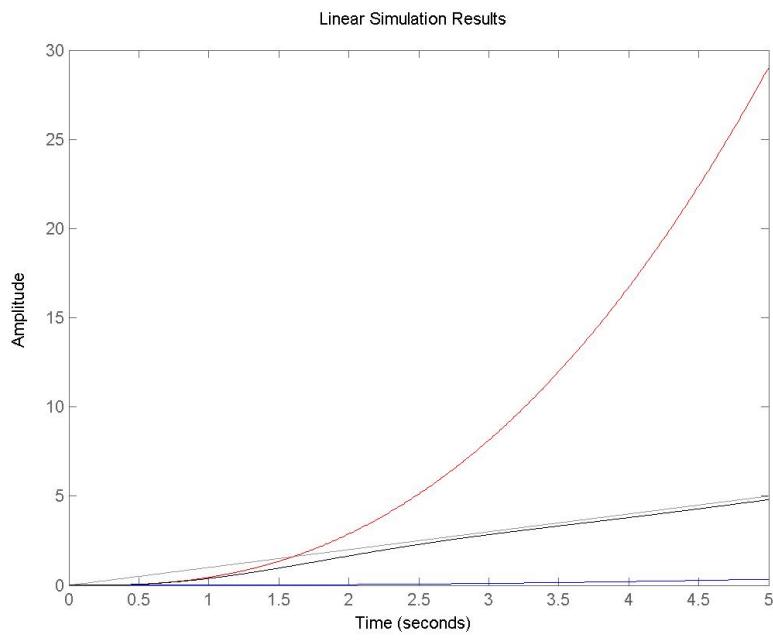


Figura 25: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

2 Exercício

$$G(s) = \frac{0,0374}{s(0,01s+1)(0,657s+1)}$$

$$\begin{cases} M_{f\text{desejada}} = 45^\circ \\ e_ss = 0,5\% = 0,005 \end{cases}$$

2.1 Ajuste do ganho

$$K_v = \frac{1}{e_{ss}} = \lim_{s \rightarrow 0} s K_c G_{av}(s) G(s)$$

$$\frac{1}{0,005} = \lim_{s \rightarrow 0} s K_c \frac{T_1 s + 1}{\alpha T_1 s + 1} \frac{0,0374}{s(0,01s+1)(0,657s+1)}$$

$$200 = 0K_c \frac{T_1 \cdot 0 + 1}{\alpha T_1 \cdot 0 + 1} \frac{0,0374}{0(0,01 \cdot 0 + 1)(0,657 \cdot 0 + 1)}$$

$$200 = 0,0374 K_c \Rightarrow \begin{cases} K_c = 5347,59 \\ K_v = 200 \end{cases}$$

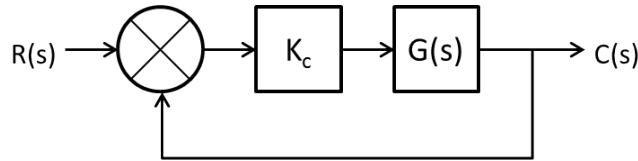


Figura 26: Diagrama de blocos do sistema com ganho ajustado

$$K_c G(s) = \frac{200}{s(0,01s+1)(0,657s+1)}$$

$$\begin{cases} M_{f\text{atual}} = -4,77^\circ \\ \omega_{cg} = 17,3 \text{ rad/s} \end{cases}$$

2.2 Ângulo de avanço

$$\phi_m = M_{f\text{desejada}} - M_{f\text{atual}} + t_{olerância}$$

$$\phi_m = 45^\circ - (-4,77^\circ) + 10^\circ = 59,77^\circ$$

2.3 Fator de atenuação

$$\phi_m = \arcsin \frac{1 - \alpha}{1 + \alpha} \Rightarrow \sin \phi_m = \frac{1 - \alpha}{1 + \alpha} \Rightarrow \alpha = \frac{1 - \sin \phi_m}{1 + \sin \phi_m}$$

$$\alpha = \frac{1 - \sin 59,77}{1 + \sin 59,77} = 0,073$$

$$-20 \log \left(\frac{1}{\sqrt{\alpha}} \right) = -20 \log \left(\frac{1}{\sqrt{0,073}} \right) = -11,37 dB$$

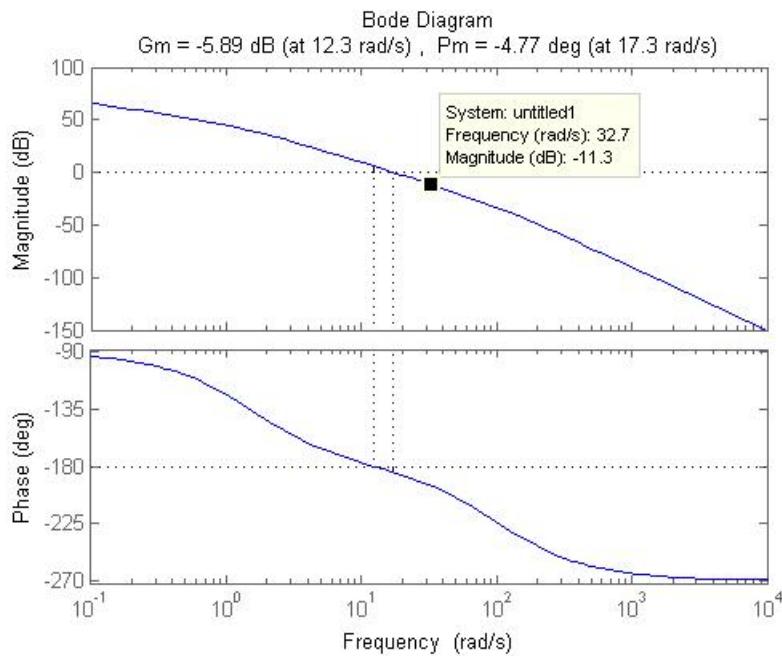


Figura 27: Frequência de defasagem máxima

$$\omega_m \approx 32.7 rad/s$$

2.4 Polos e zeros do compensador

$$\omega_m = \frac{1}{\sqrt{\alpha} T} \Rightarrow T = \frac{1}{\omega_m \sqrt{\alpha}}$$

$$T = \frac{1}{32,7 \sqrt{0,073}} \cong 0,1132$$

$$\begin{cases} T = 0,1132 & (\text{zero}) \\ \alpha T = 0,0083 & (\text{polo}) \end{cases}$$

2.5 Compensador por avanço de fase

$$K_c G_{av}(s) G(s) = K_c \frac{Ts + 1}{\alpha Ts + 1} \frac{0,0374}{s(0,01s + 1)(0,657s + 1)}$$

$$K_c G_{av}(s) G(s) = 5347,59 \frac{0,1132s + 1}{0,0083s + 1} \frac{0,0374}{s(0,01s + 1)(0,657s + 1)}$$

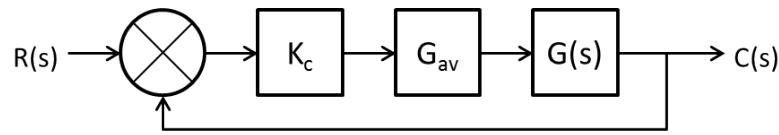


Figura 28: Diagrama de blocos do sistema controlado por avanço de fase

$$K_c G_{av}(s) G(s) = \frac{22,64s + 200}{(5,427 \cdot 10^{-5})s^4 + 0,0121s^3 + 0,6573s^2 + s}$$

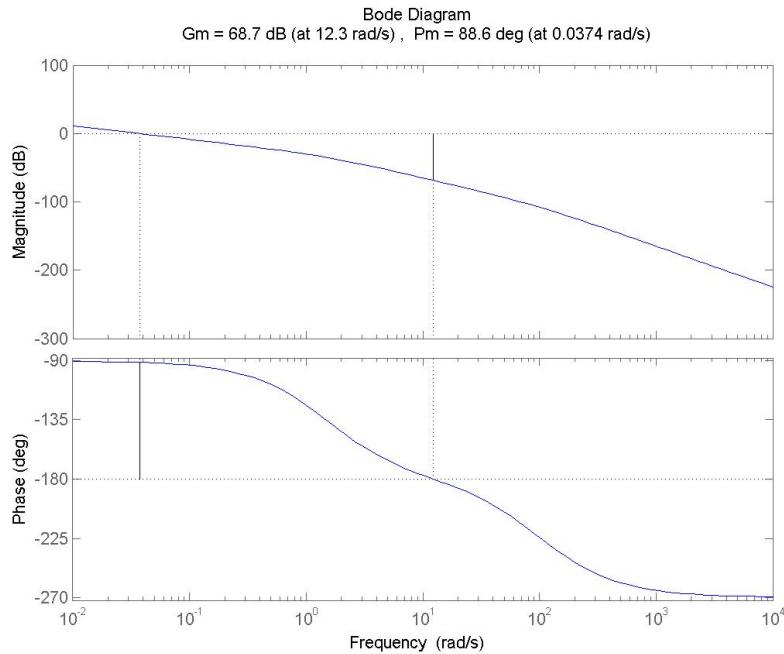


Figura 29: Diagrama de Bode do sistema sem compensação

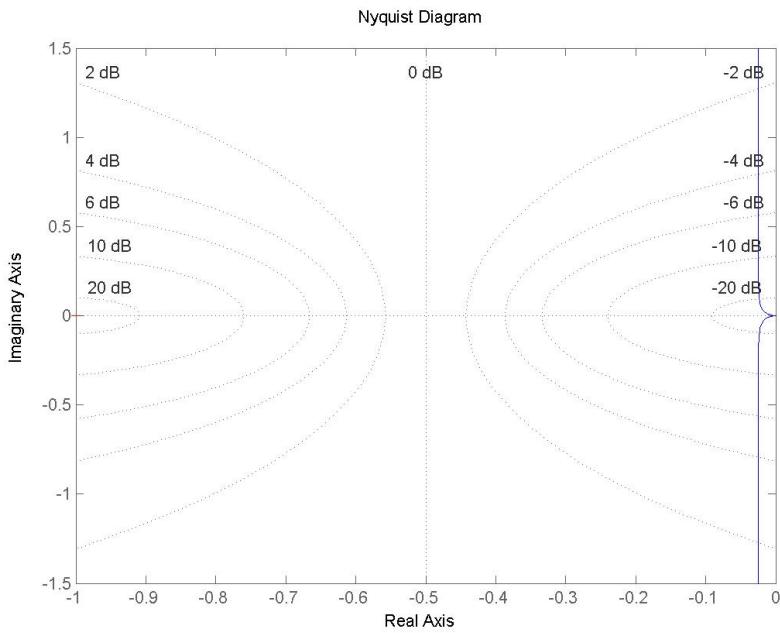


Figura 30: Diagrama de Nyquist do sistema sem compensaço

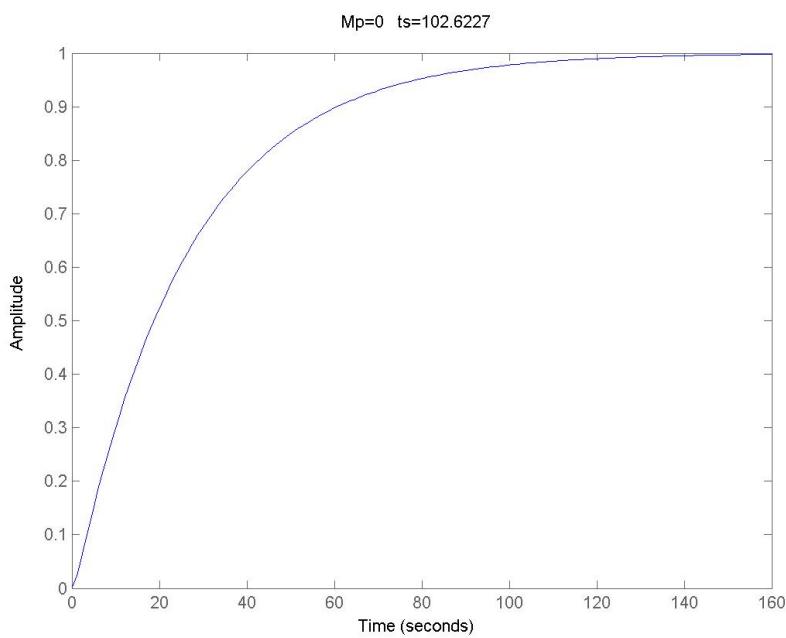


Figura 31: Resposta do sistema ao degrau unitrio sem compensaço

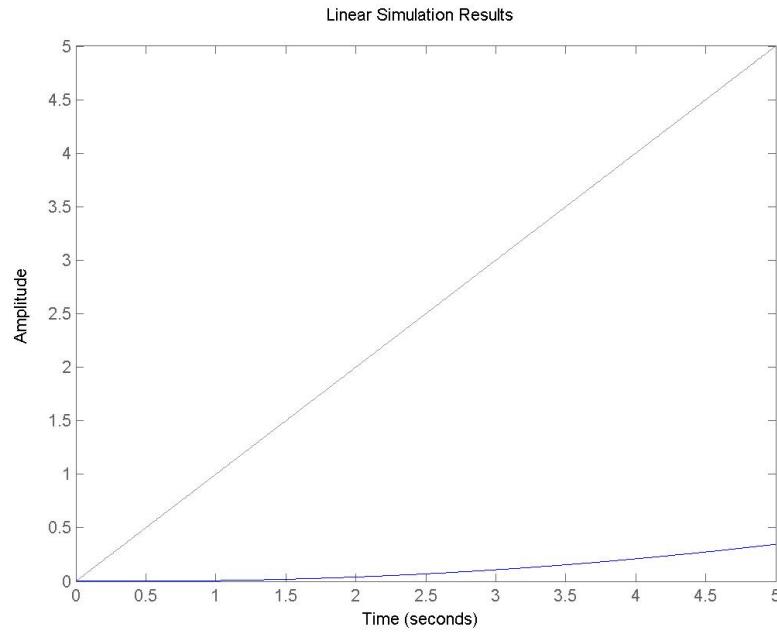


Figura 32: Resposta do sistema a rampa unitária sem compensação

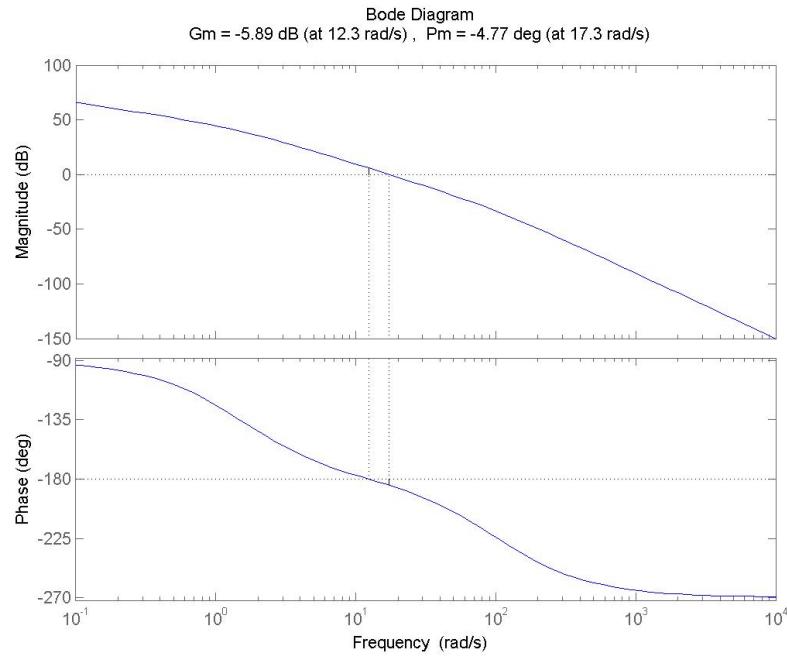


Figura 33: Diagrama de Bode do sistema com ajuste de ganho

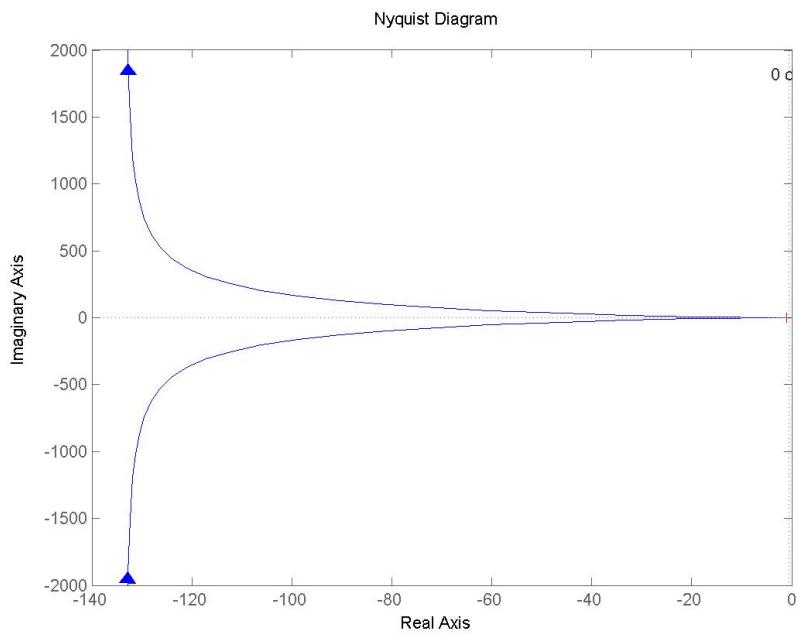


Figura 34: Diagrama de Nyquist do sistema com ajuste de ganho

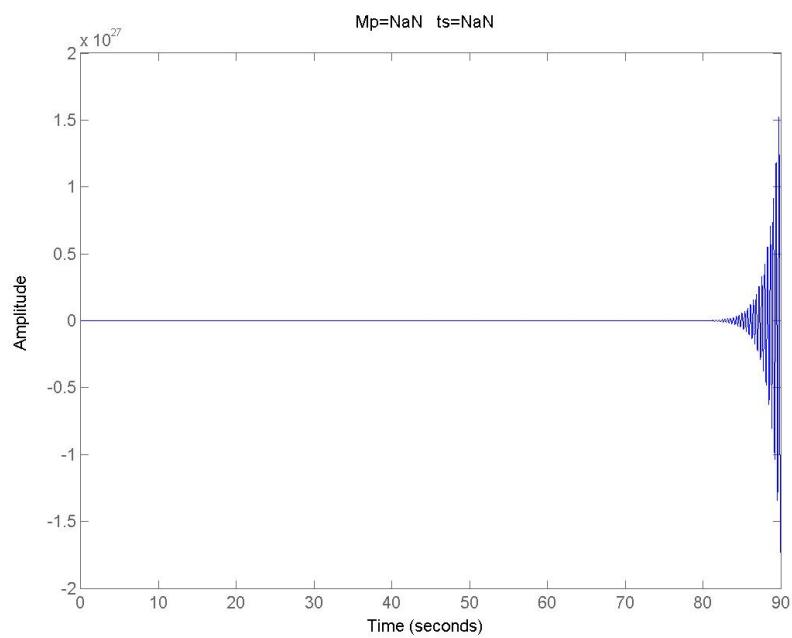


Figura 35: Resposta do sistema ao degrau unitário com ajuste de ganho

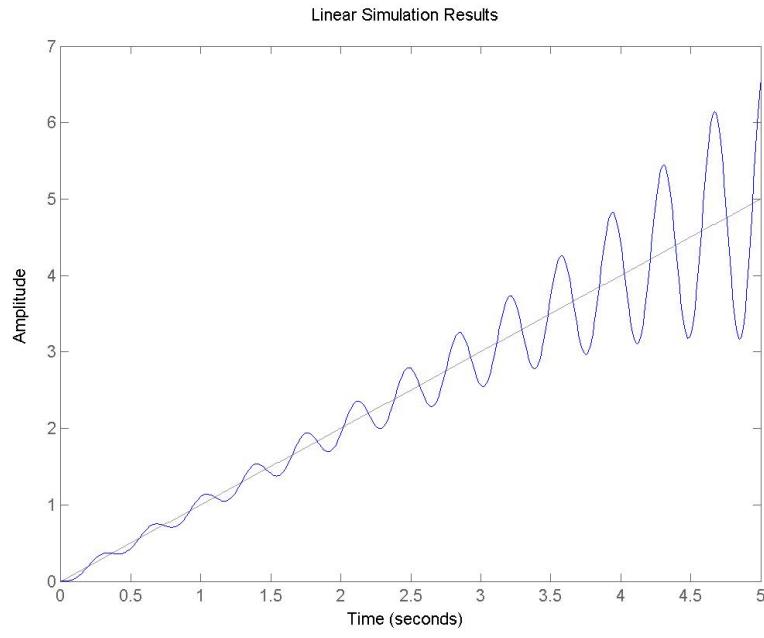


Figura 36: Resposta do sistema a rampa unitária com ajuste de ganho

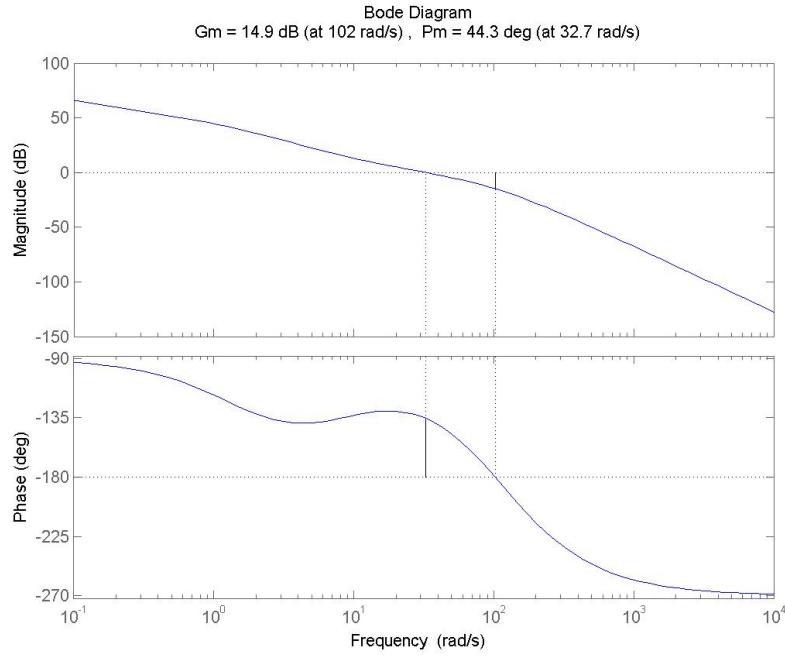


Figura 37: Diagrama de Bode do sistema com avanço de fase

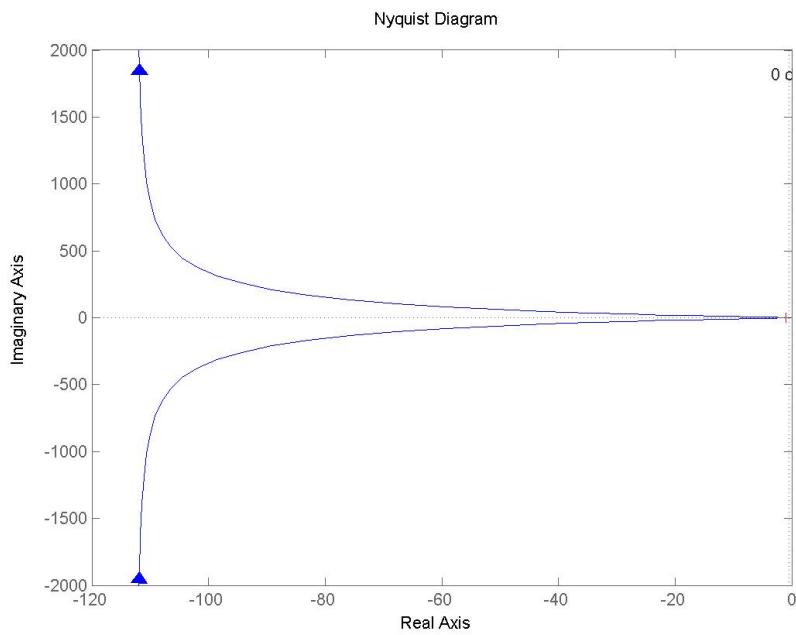


Figura 38: Diagrama de Nyquist do sistema com avanço de fase

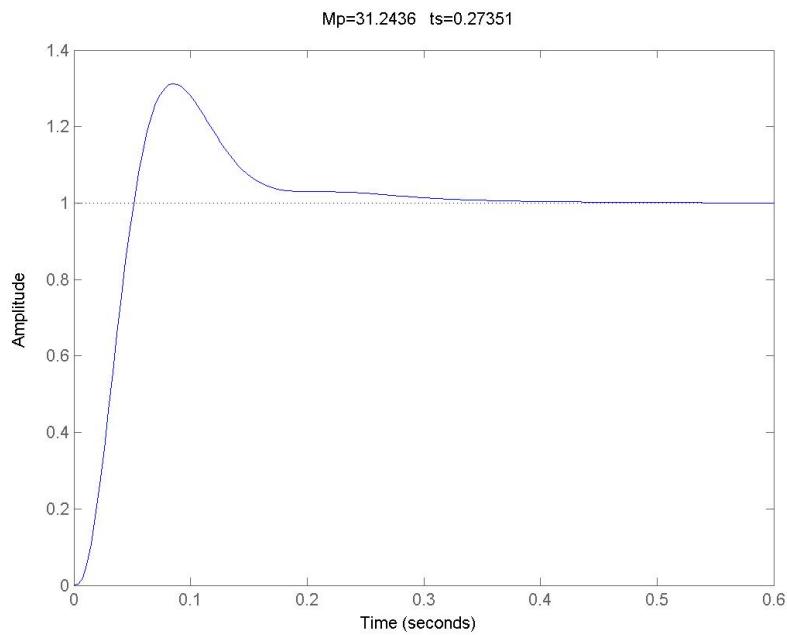


Figura 39: Resposta do sistema ao degrau unitário compensado por avanço

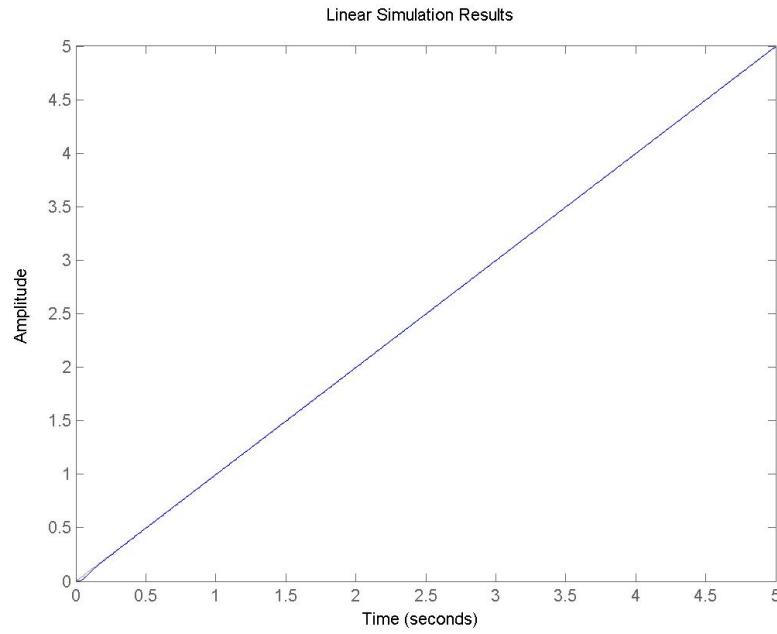


Figura 40: Resposta do sistema a rampa unitária compensado por avanço

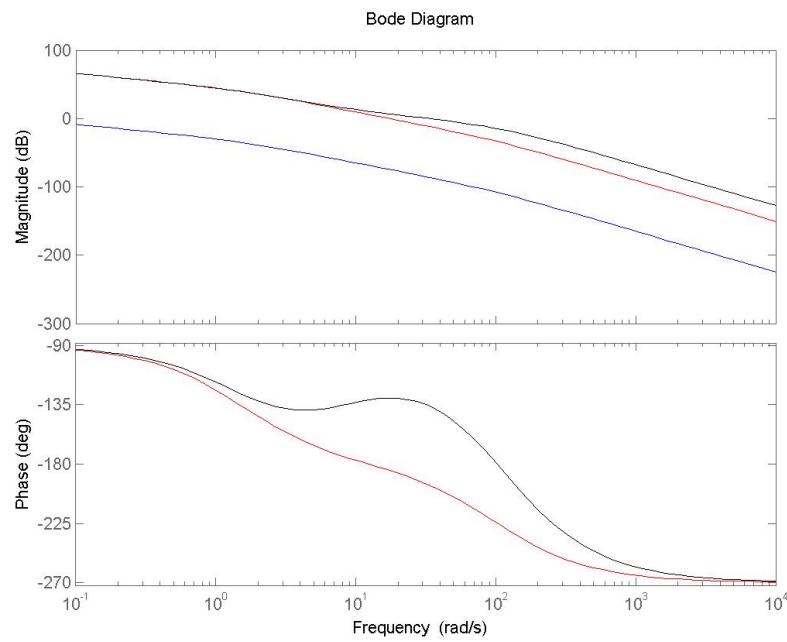


Figura 41: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

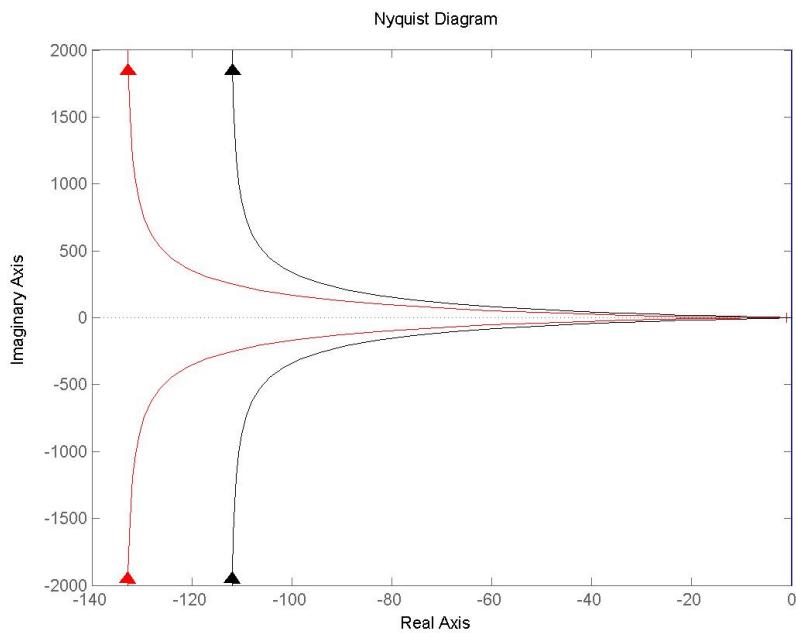


Figura 42: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

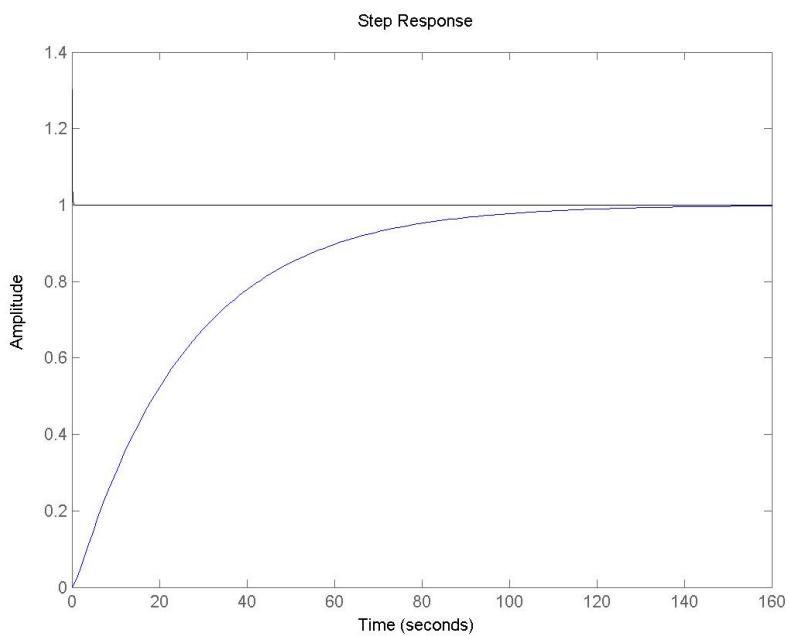


Figura 43: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

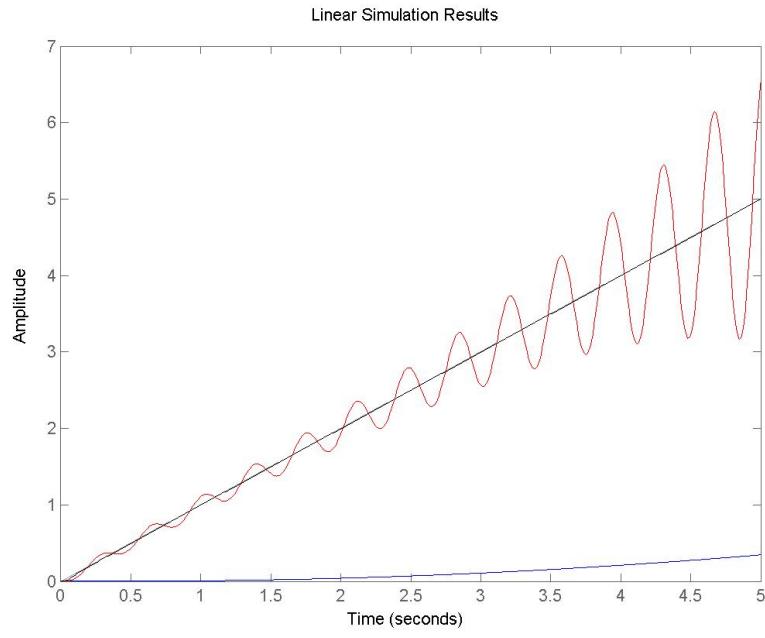


Figura 44: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

3 Exercício

$$G(s) = \frac{K}{s+3}$$

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

$$\begin{cases} t_{s2\%} = 1s \\ M_p = 5\% = 0,05 \end{cases}$$

$$\xi_{desejada} = \frac{-\ln(M_p)}{\sqrt{\pi^2 + [\ln(M_p)]^2}} = \frac{-\ln(0,05)}{\sqrt{\pi^2 + [\ln(0,05)]^2}} \approx 0,6901$$

$$t_{s2\%} = \frac{4}{\xi\omega_n} \Rightarrow \omega_n = \frac{4}{\xi t_{s2\%}} = \frac{4}{0,69.1} \approx 5,7962 rad/s$$

$$G_{MF} = 1 + G_c(s).G(s) = 1 + \frac{s+a}{s} \frac{K}{s+3} = \frac{s^2 + s(K+3) + K.a}{s(s+3)} = 0$$

$$s^2 + s(K+3) + K.a = s^2 + 2\xi\omega_n s + \omega_n^2$$

$$\begin{cases} K+3 = 2\xi\omega_n \\ K.a = \omega_n^2 \end{cases} \Rightarrow \begin{cases} K+3 = 2.0,6901.5,7962 \\ K.a = 5,7962^2 \end{cases} \Rightarrow \begin{cases} K = 5 \\ a = 6,7192 \end{cases}$$

$$G_c(s) = \frac{s+6,7192}{s}$$

4 Exercício

$$G(s) = \frac{2500.K_0}{s(s+25)}$$

$$\begin{cases} e_ss = 0,5\% = 0,01 \\ M_p \leq 1\% = 0,05 \\ t_r \leq 0,02 \\ t_s \leq 0,02 \end{cases}$$

4.1 Ajuste do ganho

$$K_v = \frac{1}{e_{ss}} = \lim_{s \rightarrow 0} s K_c G_{av}(s) G(s)$$

$$\frac{1}{0,01} = \lim_{s \rightarrow 0} s K_c \frac{T_1 s + 1}{\alpha T_1 s + 1} \frac{2500.K_0}{s(s+25)}$$

$$\frac{1}{0,01} = 0K_c \frac{T_1.0 + 1}{\alpha T_1.0 + 1} \frac{2500.K_0}{0(0+25)}$$

$$100 = \frac{2500.K_c}{25} \Rightarrow \begin{cases} K_c = 1 \\ K_v = 100 \end{cases}$$

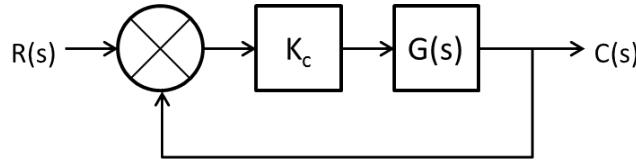


Figura 45: Diagrama de blocos do sistema com ganho ajustado

$$K_c G(s) = \frac{100}{s(\frac{s}{25} + 1)}$$

4.2 Margem de fase

$$\xi_{desejada} = \frac{-\ln(M_p)}{\sqrt{\pi^2 + [\ln(M_p)]^2}} = \frac{-\ln(0,05)}{\sqrt{\pi^2 + [\ln(0,05)]^2}} \approx 0,6901$$

$$M_{f desejada} = 100\xi = 69^\circ$$

$$\begin{cases} M_{fatual} = 28^\circ \\ \omega_{cg} = 47 rad/s \end{cases}$$

4.3 Ângulo de avanço

$$\phi_m = M_{f\text{desejada}} - M_{f\text{atual}} + t_{\text{olerância}}$$

$$\phi_m = 69^\circ - (28^\circ) + 5^\circ = 46^\circ$$

4.4 Fator de atenuação

$$\phi_m = \arcsin \frac{1 - \alpha}{1 + \alpha} \Rightarrow \sin \phi_m = \frac{1 - \alpha}{1 + \alpha} \Rightarrow \alpha = \frac{1 - \sin \alpha}{1 + \sin \alpha}$$

$$\alpha = \frac{1 - \sin 46}{1 + \sin 46} = 0,1632$$

$$-20 \log \left(\frac{1}{\sqrt{\alpha}} \right) = -20 \log \left(\frac{1}{\sqrt{0,1632}} \right) = -7,8741 dB$$

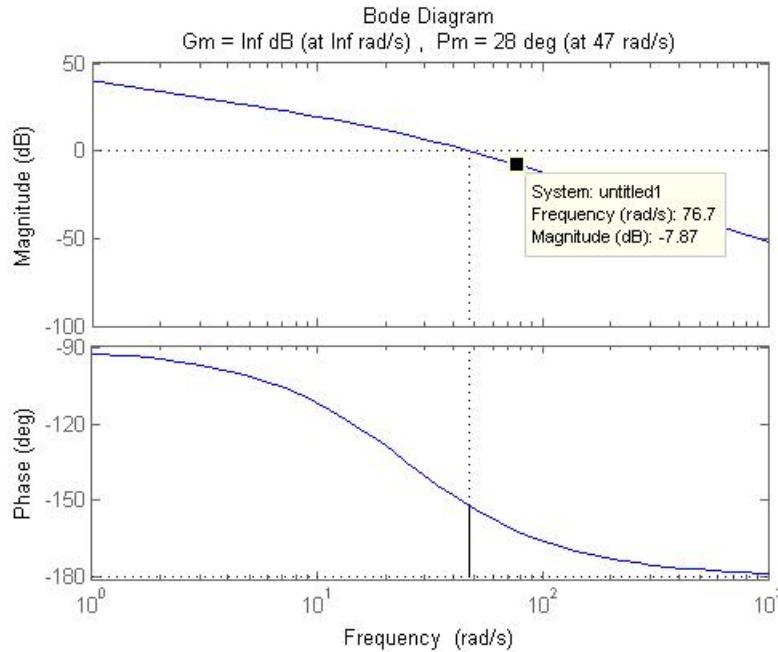


Figura 46: Frequência de defasagem máxima

$$\omega_m \approx 76,7 rad/s$$

4.5 Polos e zeros do compensador

$$\omega_m = \frac{1}{\sqrt{\alpha T}} \Rightarrow T = \frac{1}{\omega_m \sqrt{\alpha}}$$

$$T = \frac{1}{76,6\sqrt{0,1632}} \cong 0,0323$$

$$\begin{cases} T = 0,0323 & (\text{zero}) \\ \alpha T = 0,0053 & (\text{polo}) \end{cases}$$

4.6 Compensador por avanço de fase

$$K_c G_{av}(s) G(s) = K_c \frac{Ts + 1}{\alpha Ts + 1} \frac{2500}{s(s + 25)}$$

$$K_c G_{av}(s) G(s) = \frac{0,0323s + 1}{0,0053s + 1} \frac{2500}{s(s + 25)}$$

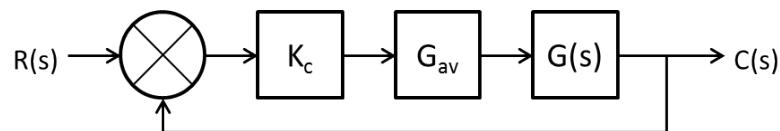


Figura 47: Diagrama de blocos do sistema controlado por avanço de fase

$$K_c G_{av}(s) G(s) = \frac{80s + 2500}{0,005266s^3 + 1,132s^2 + 25s}$$

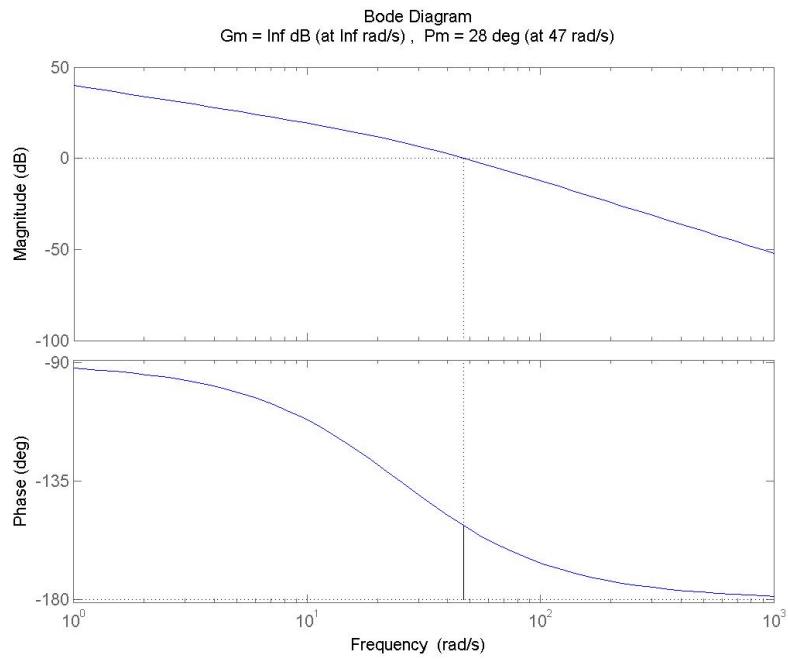


Figura 48: Diagrama de Bode do sistema sem compensação

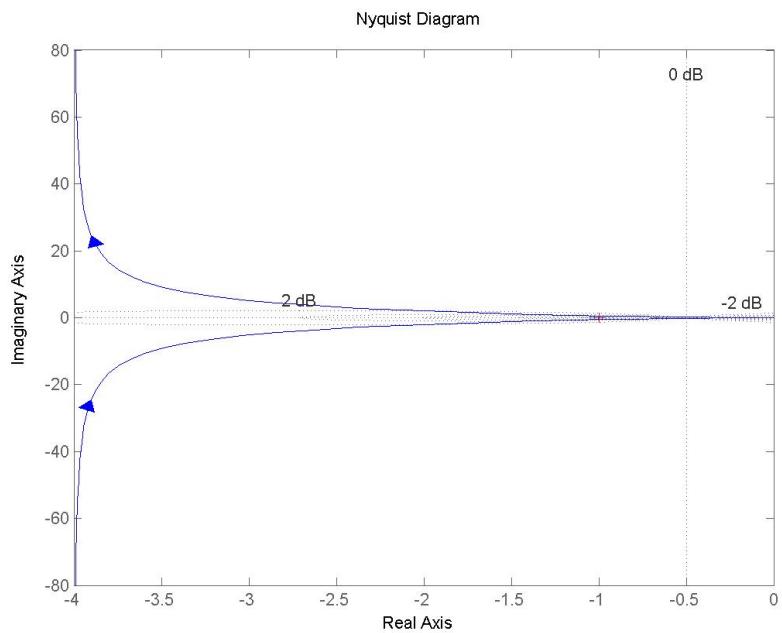


Figura 49: Diagrama de Nyquist do sistema sem compensação

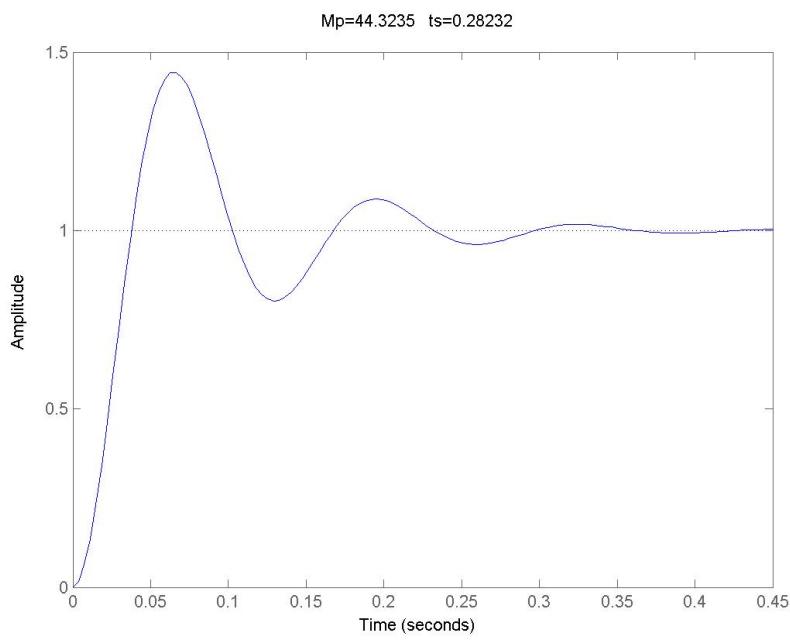


Figura 50: Resposta do sistema ao degrau unitário sem compensação

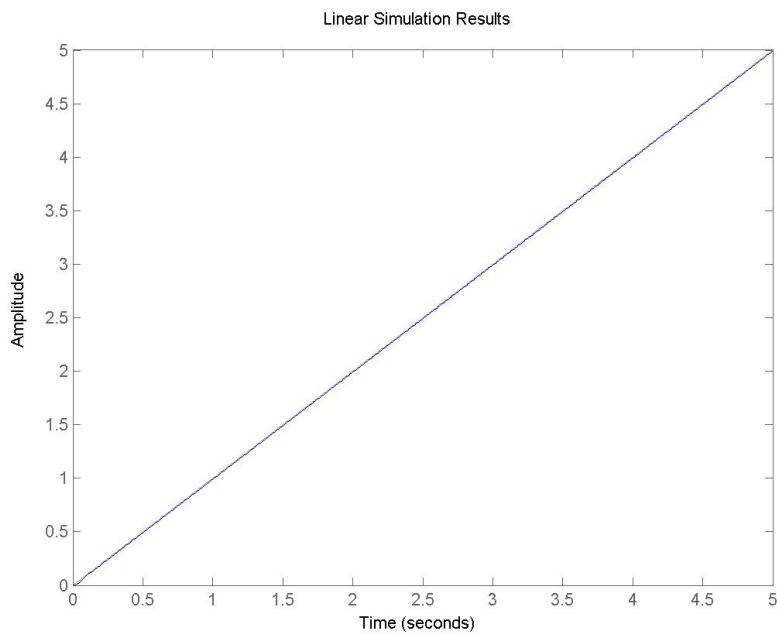


Figura 51: Resposta do sistema a rampa unitária sem compensação

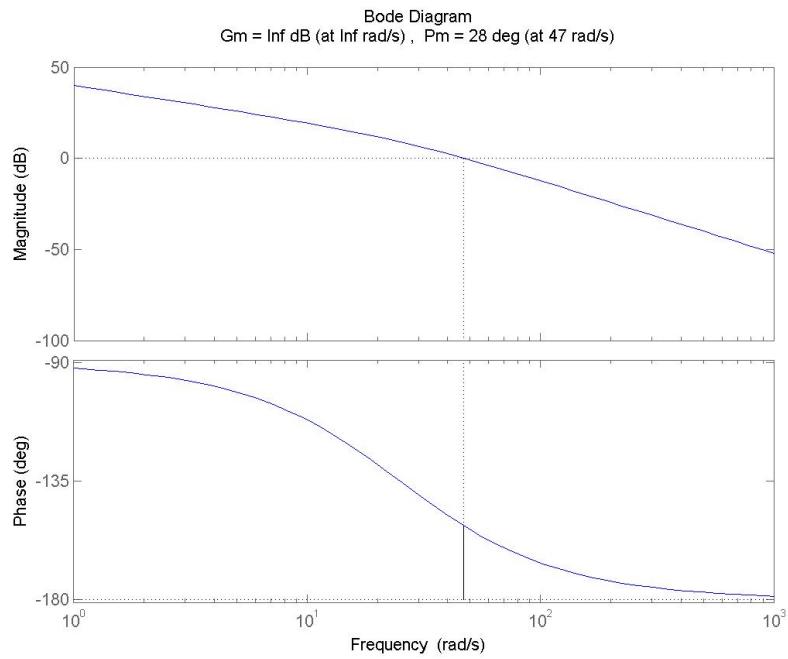


Figura 52: Diagrama de Bode do sistema com ajuste de ganho

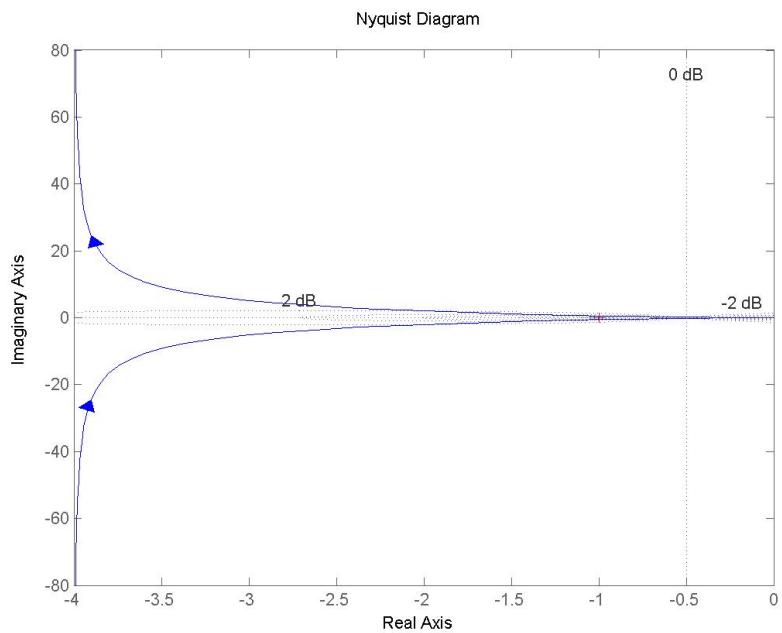


Figura 53: Diagrama de Nyquist do sistema com ajuste de ganho

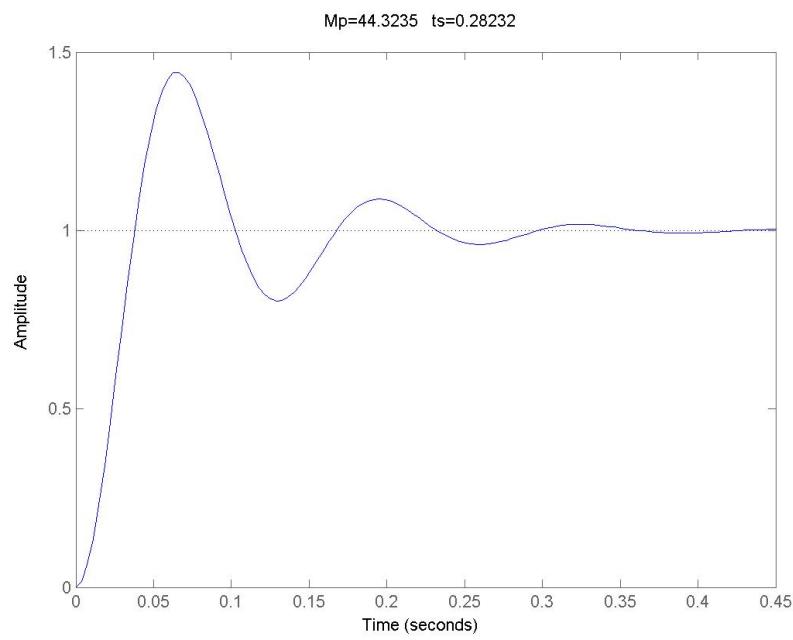


Figura 54: Resposta do sistema ao degrau unitário com ajuste de ganho

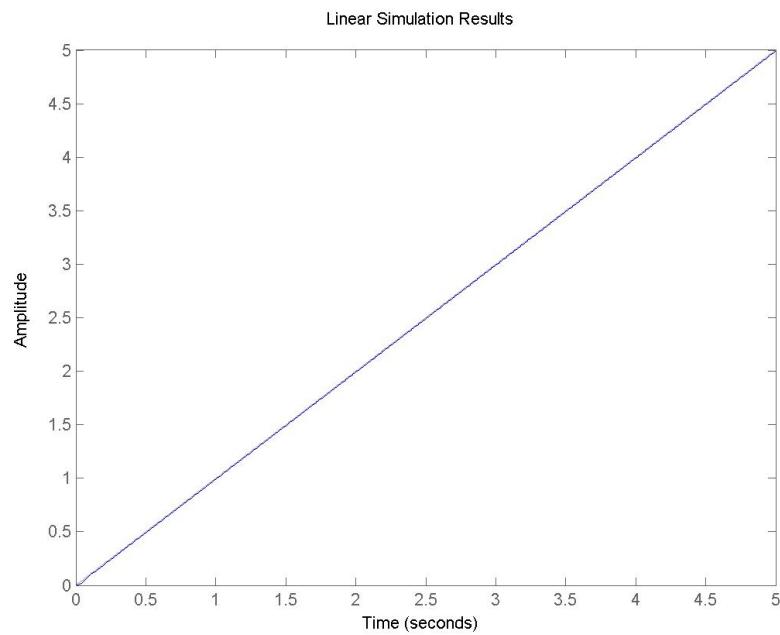


Figura 55: Resposta do sistema a rampa unitária com ajuste de ganho

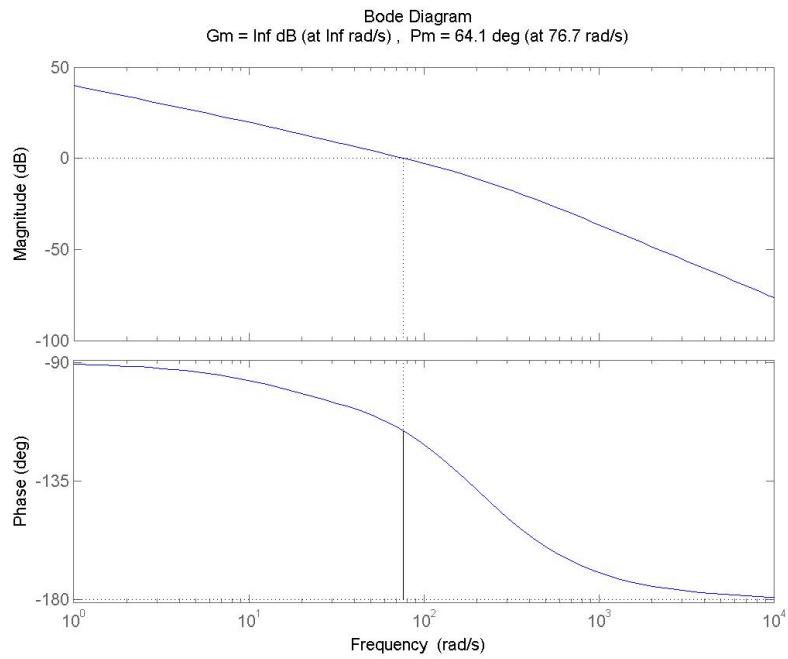


Figura 56: Diagrama de Bode do sistema com avanço de fase

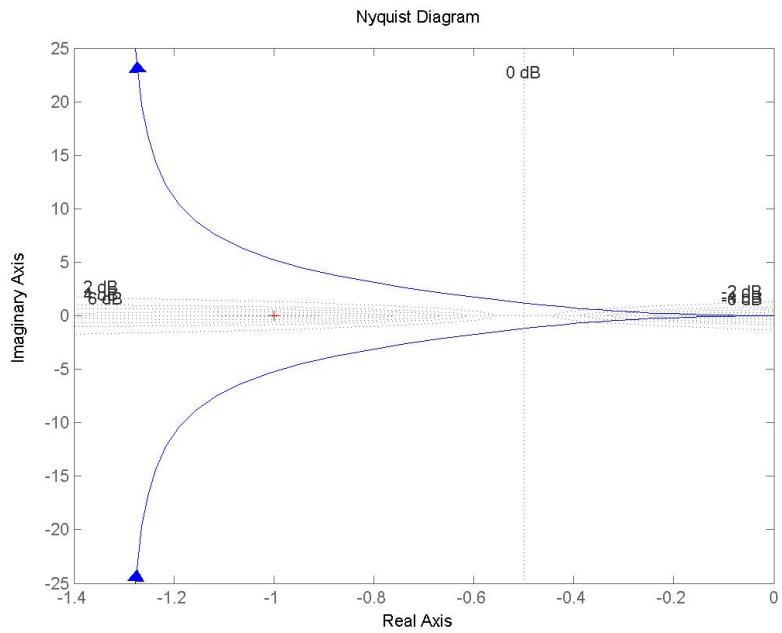


Figura 57: Diagrama de Nyquist do sistema com avanço de fase

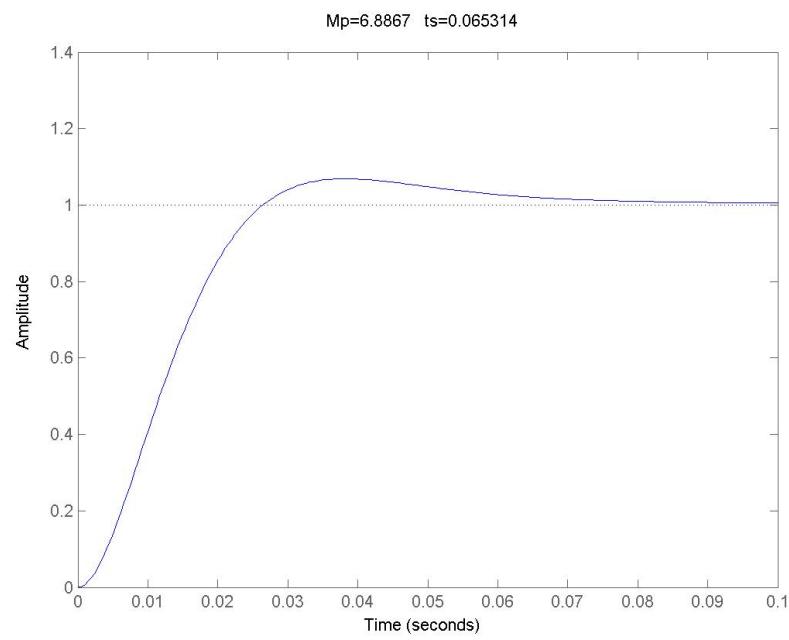


Figura 58: Resposta do sistema ao degrau unitário compensado por avanço

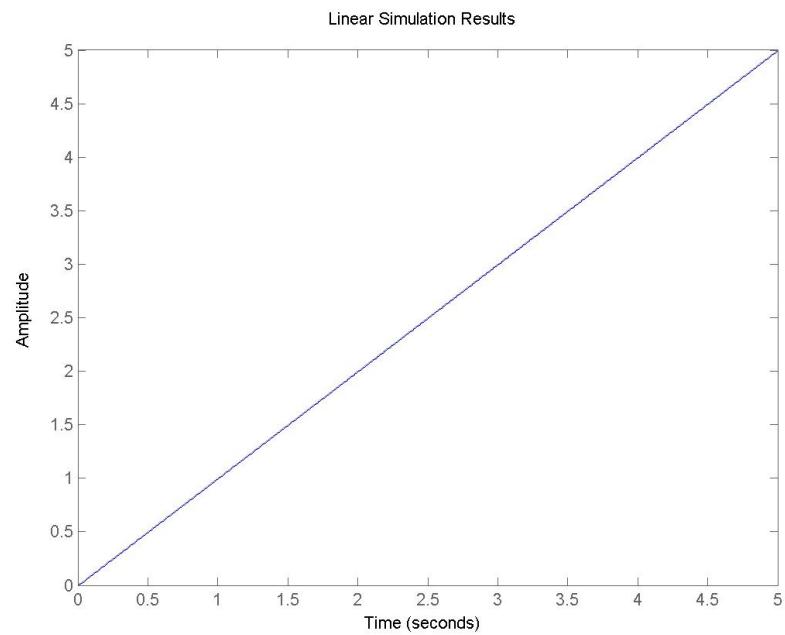


Figura 59: Resposta do sistema a rampa unitária compensado por avanço

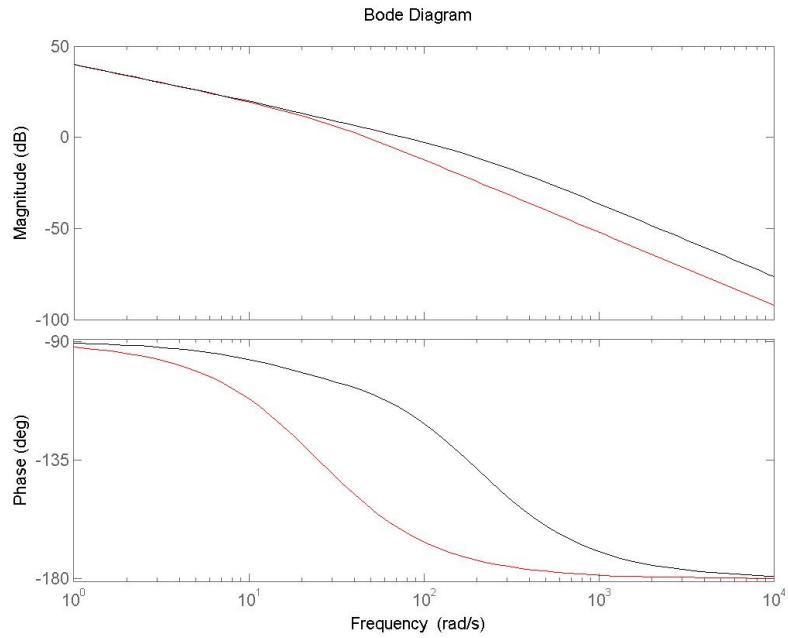


Figura 60: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

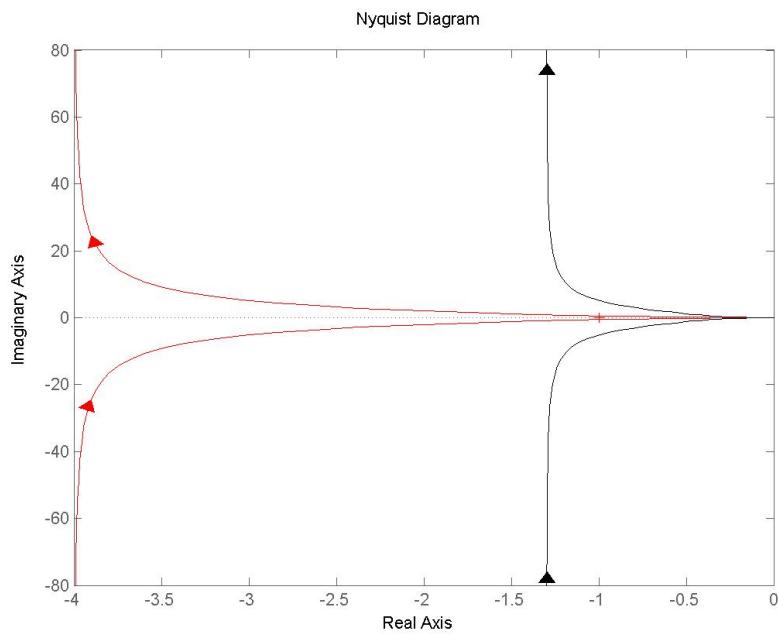


Figura 61: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

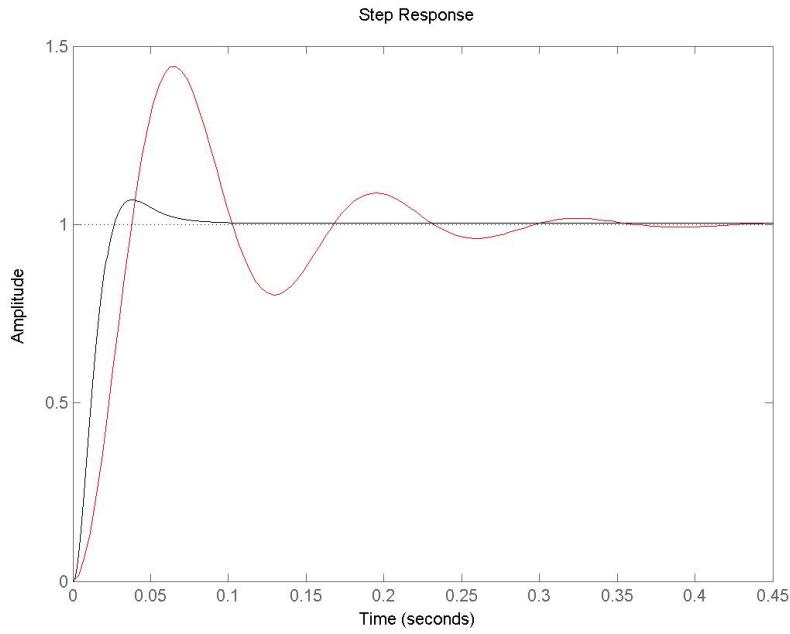


Figura 62: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

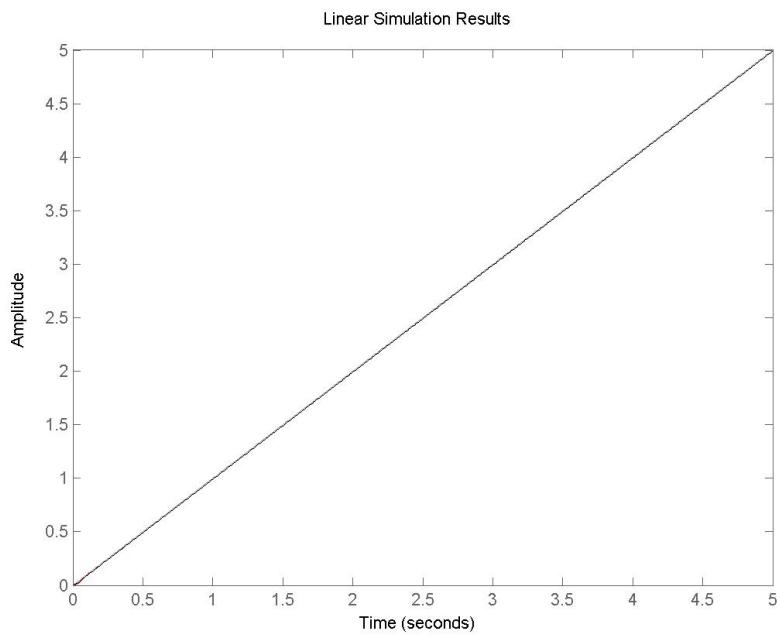


Figura 63: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

5 Exercício

$$G(s) = \frac{16(s+1)}{s(s^2 + 2s + 16)}$$

$$\begin{cases} M_p \leq 5\% = 0,05 \\ t_{s2\%} \leq 5s \end{cases}$$

5.1 Margem de fase

$$\xi_{desejada} = \frac{-\ln(M_p)}{\sqrt{\pi^2 + [\ln(M_p)]^2}} = \frac{-\ln(0,05)}{\sqrt{\pi^2 + [\ln(0,05)]^2}} \approx 0,6901$$

$$M_{f_{desejada}} = \arctan \left(\frac{2\xi}{\sqrt{-2\xi^2 + \sqrt{1 + 4\xi^4}}} \right) = \arctan 2,1084 \cong 65^\circ$$

$$\begin{cases} M_{fatual} = 30,2^\circ \\ \omega_{cg} = 5,32 rad/s \end{cases}$$

5.2 Ângulo de avanço

$$\phi_m = M_{f_{desejada}} - M_{fatual} + t_{olerância}$$

$$\phi_m = 65^\circ - (30,2^\circ) + 9^\circ = 43,4253^\circ$$

5.3 Fator de atenuação

$$\phi_m = \arcsin \frac{1-\alpha}{1+\alpha} \Rightarrow \sin \phi_m = \frac{1-\alpha}{1+\alpha} \Rightarrow \alpha = \frac{1-\sin \alpha}{1+\sin \alpha}$$

$$\alpha = \frac{1-\sin 43,4253}{1+\sin 43,4253} = 0,1853$$

$$-20 \log \left(\frac{1}{\sqrt{\alpha}} \right) = -20 \log \left(\frac{1}{\sqrt{0,1853}} \right) = -7.3224 dB$$

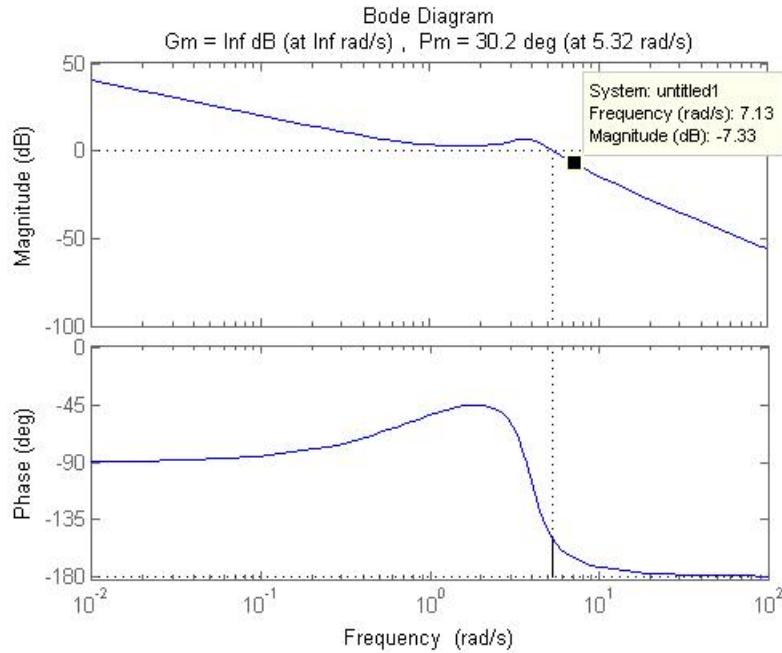


Figura 64: Frequênciade defasagem máxima

$$\omega_m \approx 7.13 \text{ rad/s}$$

5.4 Polos e zeros do compensador

$$\omega_m = \frac{1}{\sqrt{\alpha}T} \Rightarrow T = \frac{1}{\omega_m \sqrt{\alpha}}$$

$$T = \frac{1}{7,13\sqrt{0,1853}} \cong 0,3259$$

$$\begin{cases} T = 0,3529 & (\text{zero}) \\ \alpha T = 0,0604 & (\text{polo}) \end{cases}$$

5.5 Compensador por avanço de fase

$$G_{av}(s)G(s) = \frac{Ts + 1}{\alpha Ts + 1} \frac{16(s + 1)}{s(s^2 + 2s + 16)}$$

$$G_{av}(s)G(s) = \frac{0,3529s + 1}{0,0604s + 1} \frac{16(s + 1)}{s(s^2 + 2s + 16)}$$

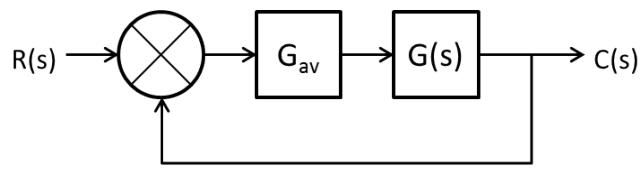


Figura 65: Diagrama de blocos do sistema compensado por avanço de fase

$$G_{av}(s)G(s) = \frac{5,214s^2 + 21,21s + 16}{0.06037s^4 + 1,121s^3 + 2,966s^2 + 16s}$$

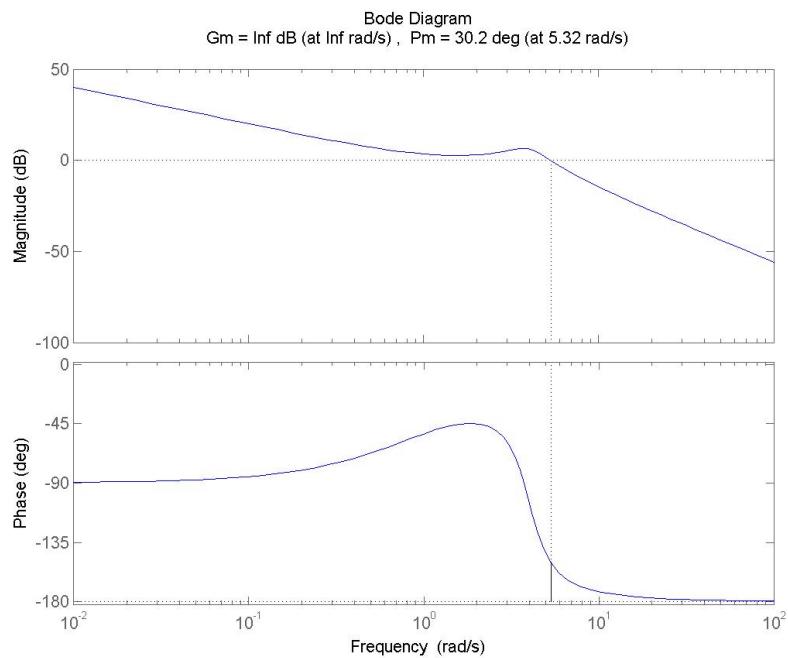


Figura 66: Diagrama de Bode do sistema sem compensação

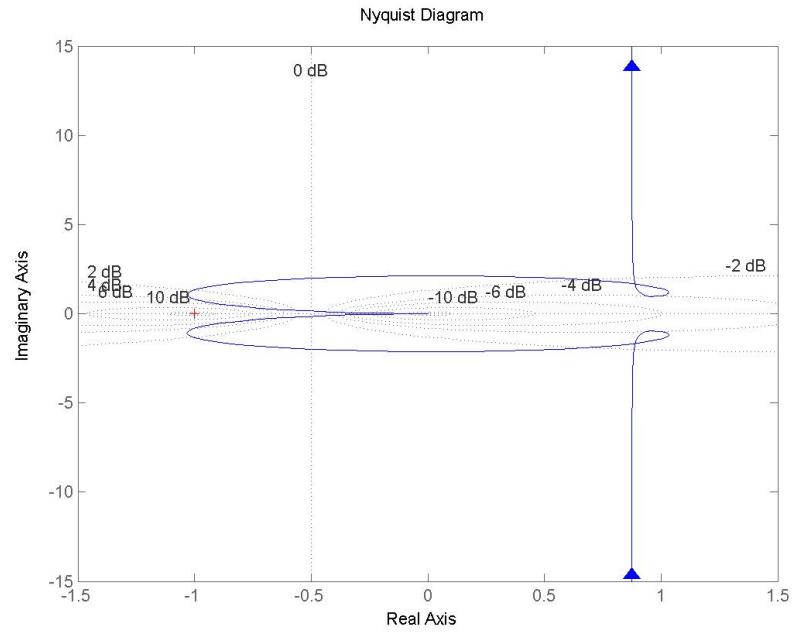


Figura 67: Diagrama de Nyquist do sistema sem compensação

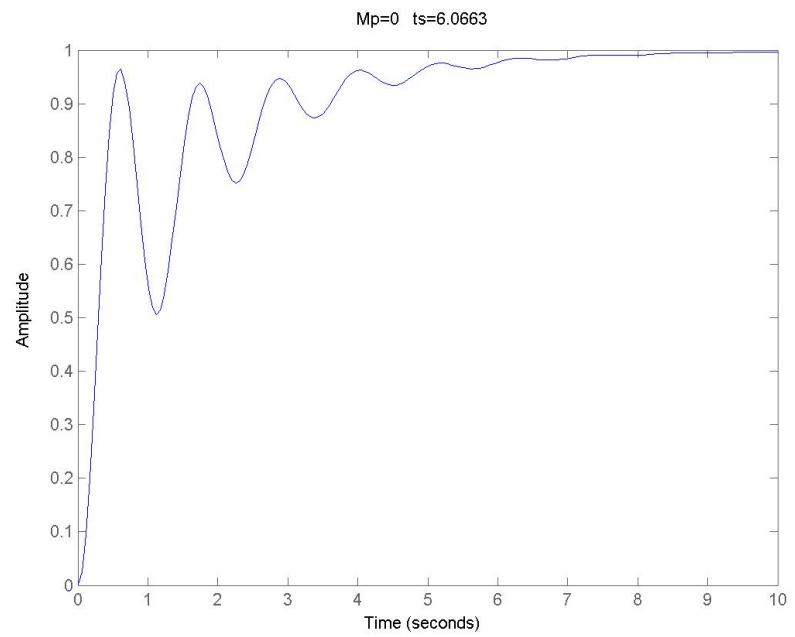


Figura 68: Resposta do sistema ao degrau unitário sem compensação

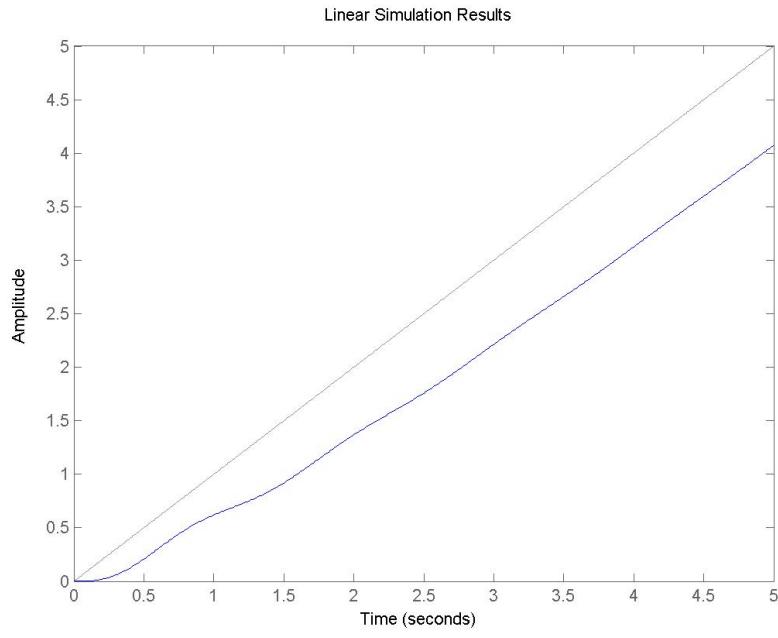


Figura 69: Resposta do sistema a rampa unitária sem compensação

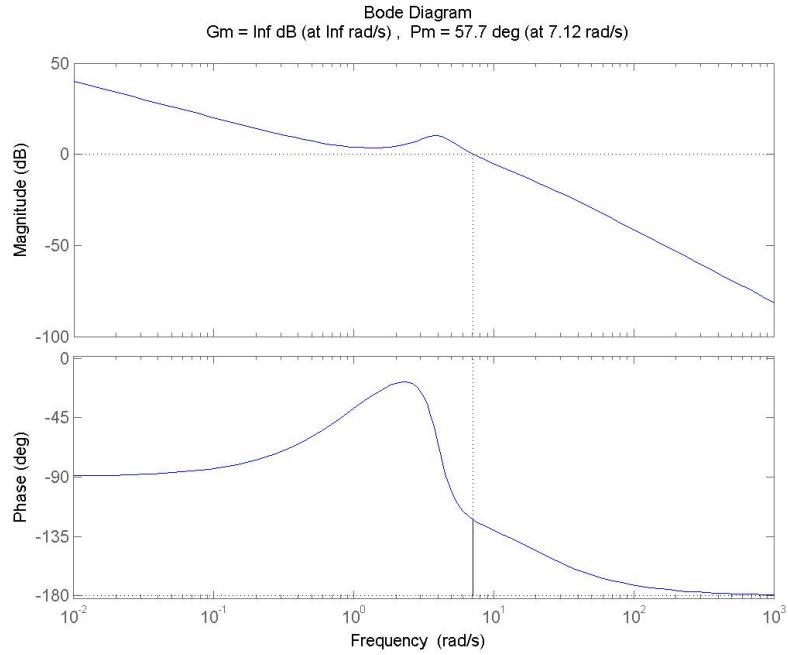


Figura 70: Diagrama de Bode do sistema com avanço de fase

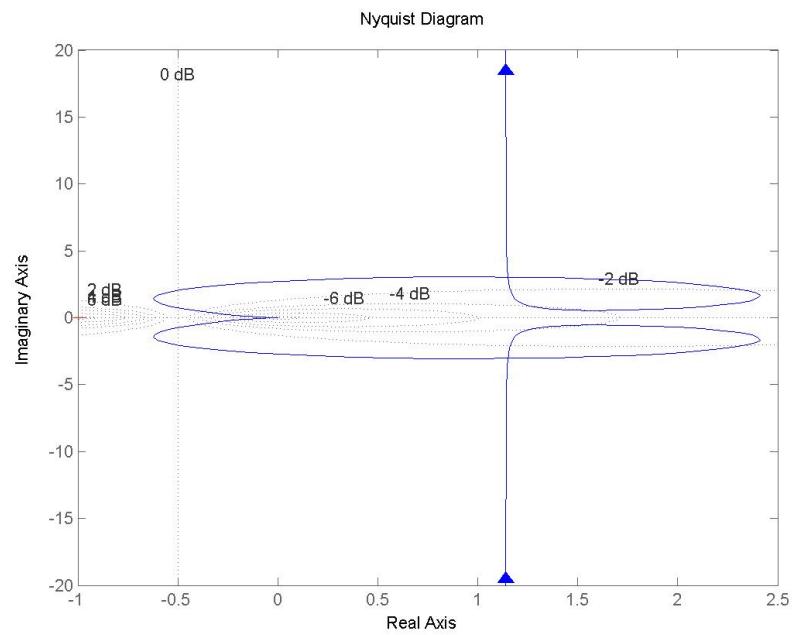


Figura 71: Diagrama de Nyquist do sistema com avanço de fase

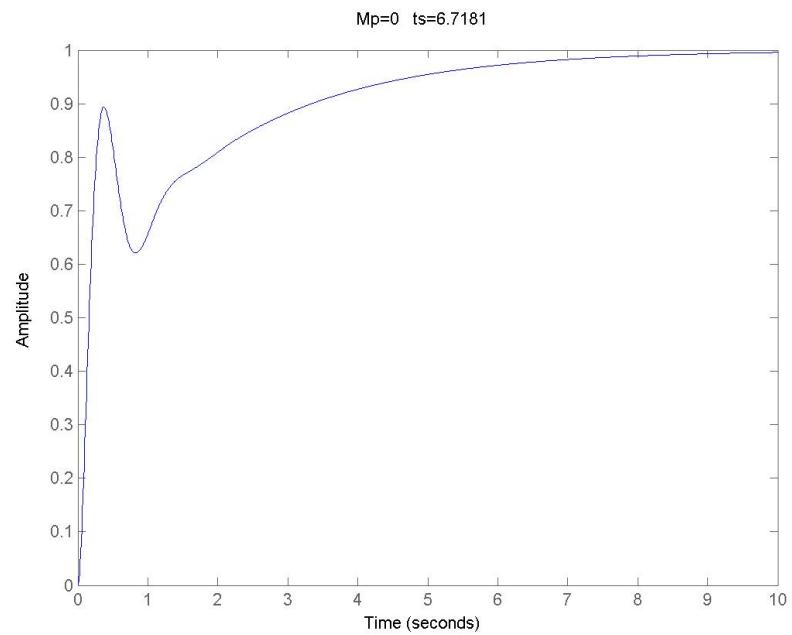


Figura 72: Resposta do sistema ao degrau unitário compensado por avanço

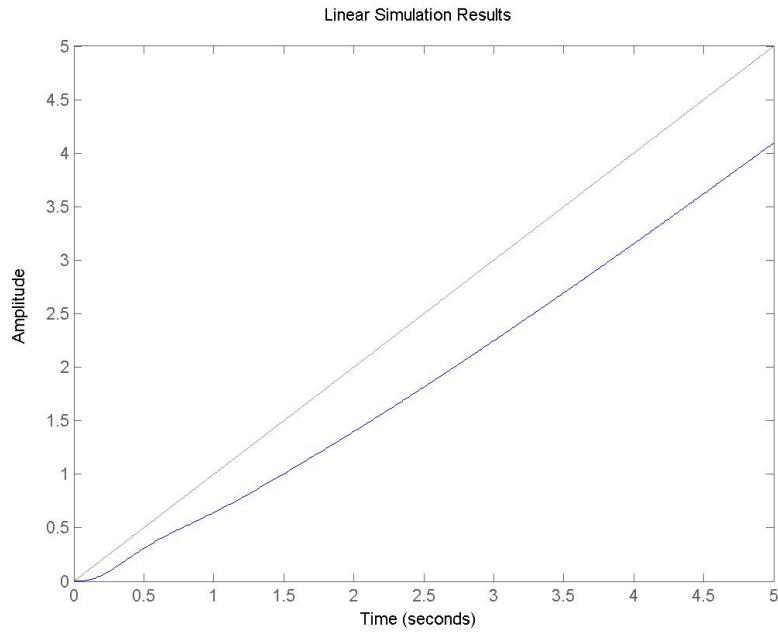


Figura 73: Resposta do sistema a rampa unitária compensado por avanço

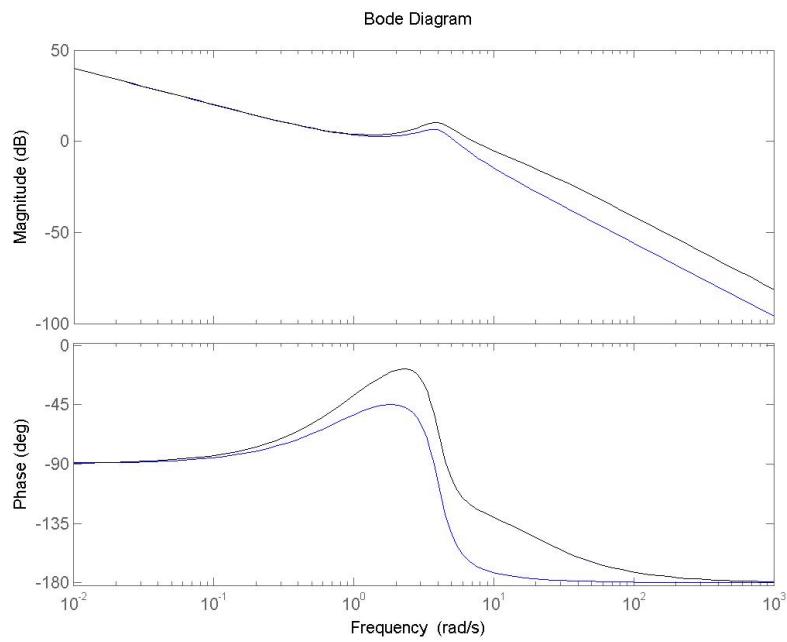


Figura 74: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

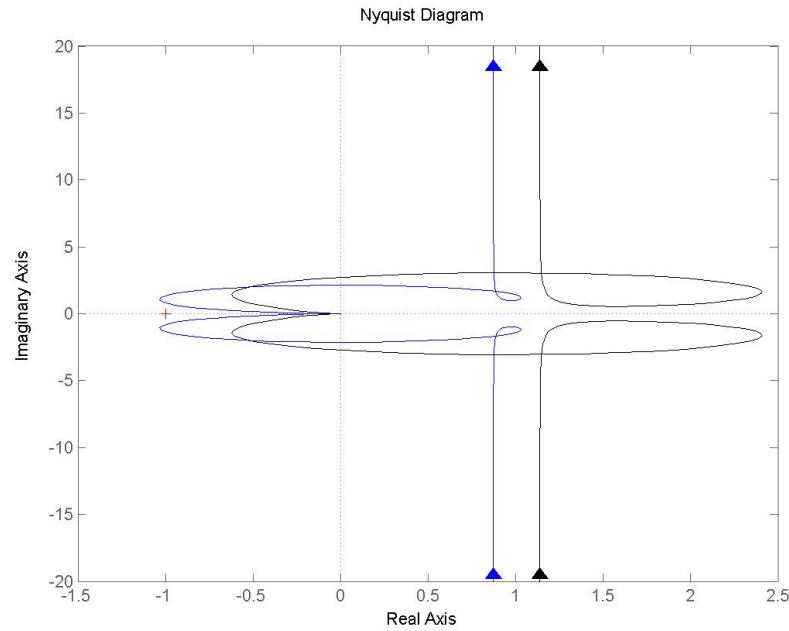


Figura 75: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

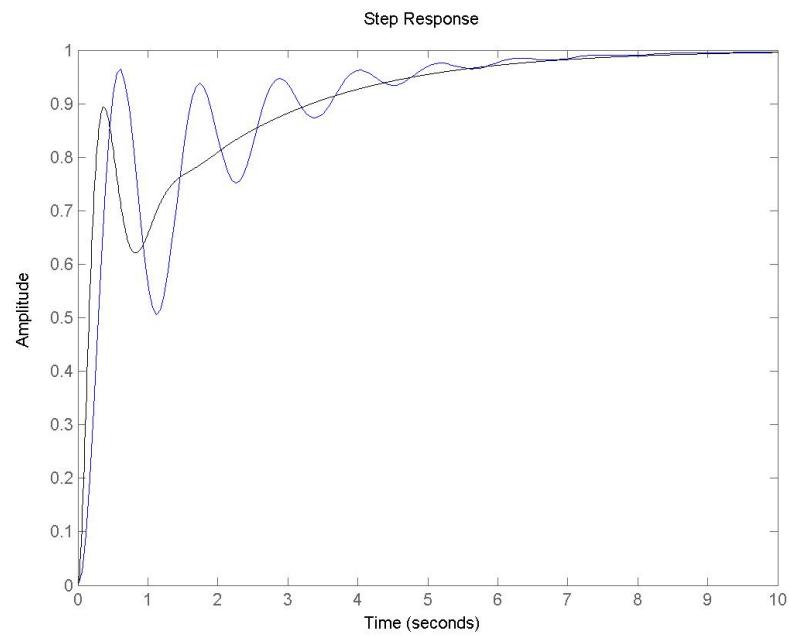


Figura 76: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

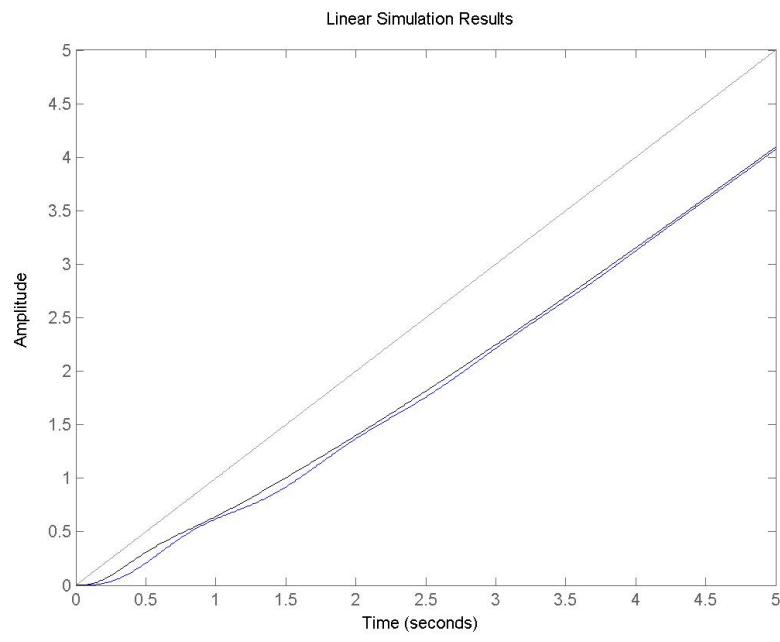


Figura 77: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

6 Exercício

$$G(s) = \frac{K_0}{s(s+10)(s+14)}$$

$$\begin{cases} e_{ss} = 10\% = 0,1 \\ \xi_{desejada} = 0,707 \end{cases}$$

6.1 Ajuste do ganho

$$K_v = \frac{1}{e_{ss}} = \lim_{s \rightarrow 0} s K_c G_{at}(s) G(s)$$

$$\frac{1}{0,1} = \lim_{s \rightarrow 0} s K_c \frac{Ts+1}{\beta Ts+1} \frac{K_0}{s(s+10)(s+14)}$$

$$10 = 0K_c \frac{T.0+1}{\beta T.0+1} \frac{K_0}{0(0+10)(0+14)}$$

$$10 = \frac{K_0 \cdot K_c}{140} \Rightarrow \begin{cases} K_0 \cdot K_c = 1400 \\ K_v = 10 \end{cases}$$

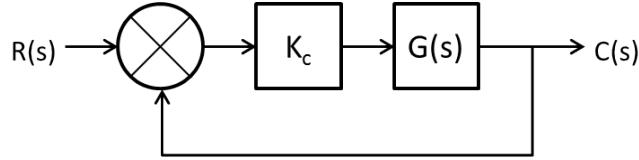


Figura 78: Diagrama de blocos do sistema com ganho ajustado

$$K_c G(s) = \frac{10}{s(\frac{s}{10} + 1)(\frac{s}{14} + 1)} \quad (1)$$

6.2 Margem de fase

$$M_{f desejada} = \arctan \left(\frac{2\xi}{\sqrt{-2\xi^2 + \sqrt{1+4\xi^4}}} \right) = \arctan 2,1968 \cong 65^\circ$$

$$\begin{cases} M_{f atual} = 27^\circ \\ \omega_{cg} = 7,21 rad/s \end{cases}$$

6.3 Ângulo de avanço

$$\phi_m = -180 + M_{f\text{desejada}} + t_{olerância}$$

$$\phi_m = -180^\circ + 65^\circ + 5^\circ = -110^\circ$$

6.4 Fator de atenuação

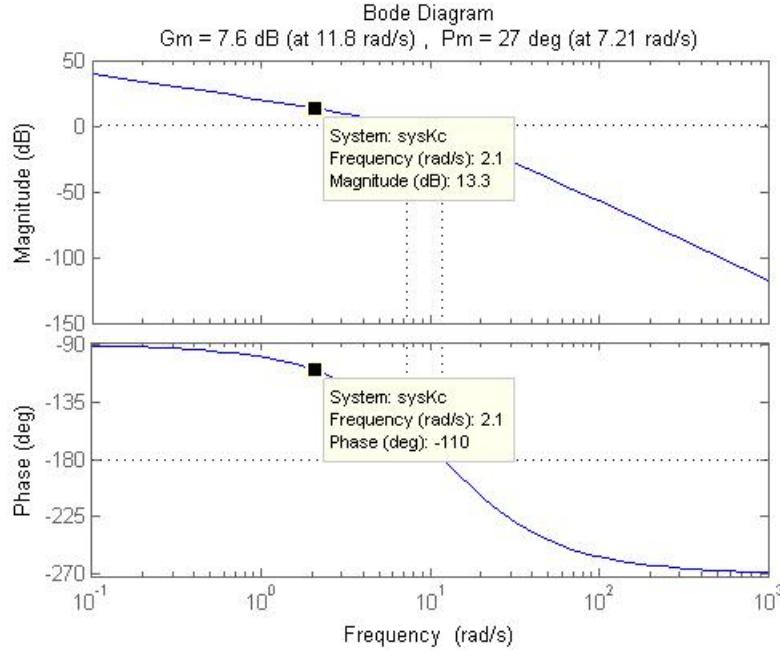


Figura 79: Frequênciа de defasagem m xima

$$\omega_m \approx 2,1 \text{ rad/s}$$

$$|G(s)|_{w=2,1} = 13,3 \text{ dB}$$

$$-20 \log \beta = -13,3 \Rightarrow \beta = 10^{13,3/20} = 4,62$$

6.5 Polos e zeros do compensador

$$\omega_m = \frac{10}{T} \Rightarrow T \Rightarrow T = \frac{10}{\omega_m} = 4,7847$$

$$\begin{cases} T = 4,7847 & (\text{zero}) \\ \beta T = 22,12 & (\text{polo}) \end{cases}$$

6.6 Compensador por atraso de fase

$$K_c G_{at}(s) G(s) = K_c \frac{Ts + 1}{\beta Ts + 1} \frac{K_0}{s(s + 10)(s + 14)}$$

$$K_c G_{at}(s) G(s) = \frac{4,7847s + 1}{22,12s + 1} \frac{1400}{s(s + 10)(s + 14)}$$

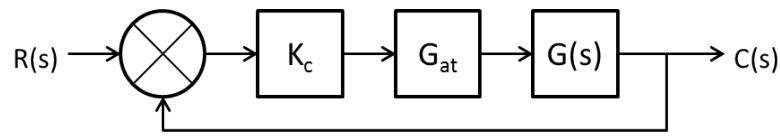


Figura 80: Diagrama de blocos do sistema compensado por atraso de fase

$$K_c G_{av}(s) G(s) = \frac{6699s + 1400}{22,12s^4 + 532s^3 + 3121s^2 + 140s}$$

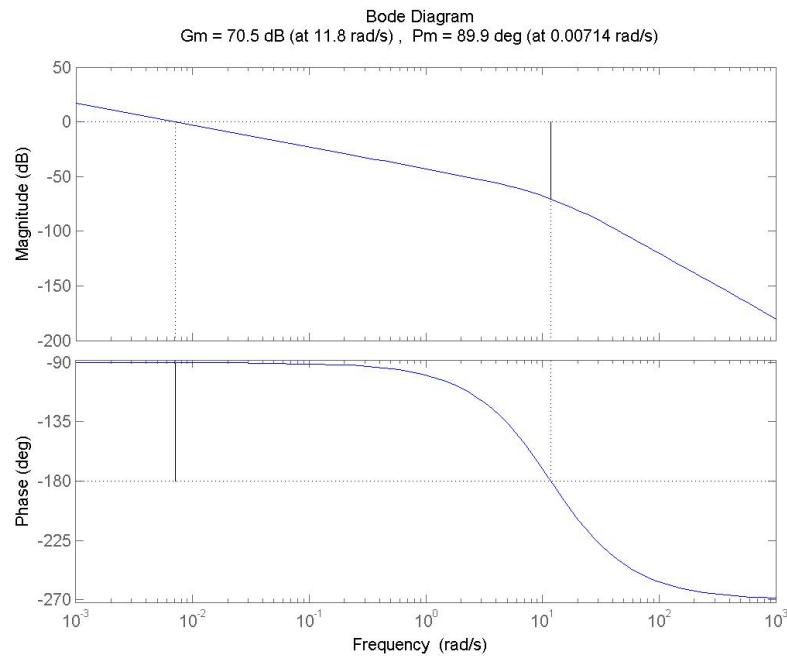


Figura 81: Diagrama de Bode do sistema sem compensação

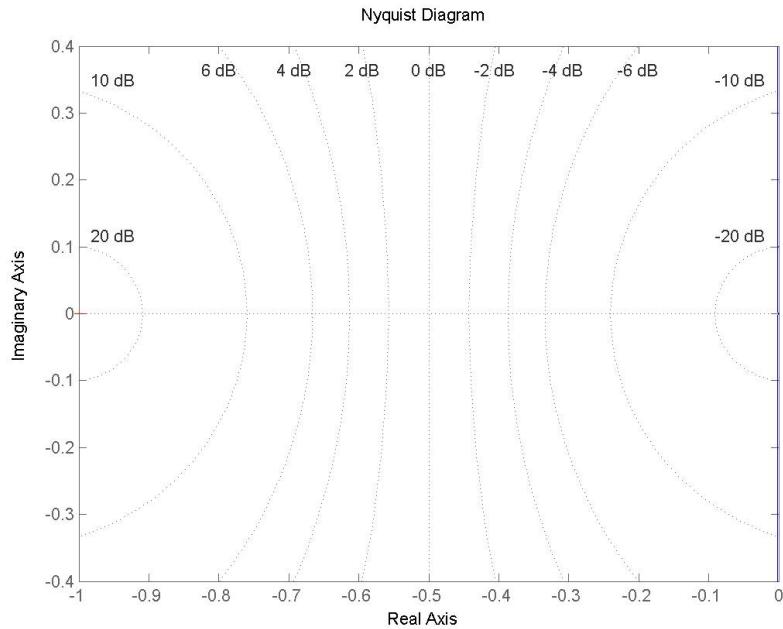


Figura 82: Diagrama de Nyquist do sistema sem compensação

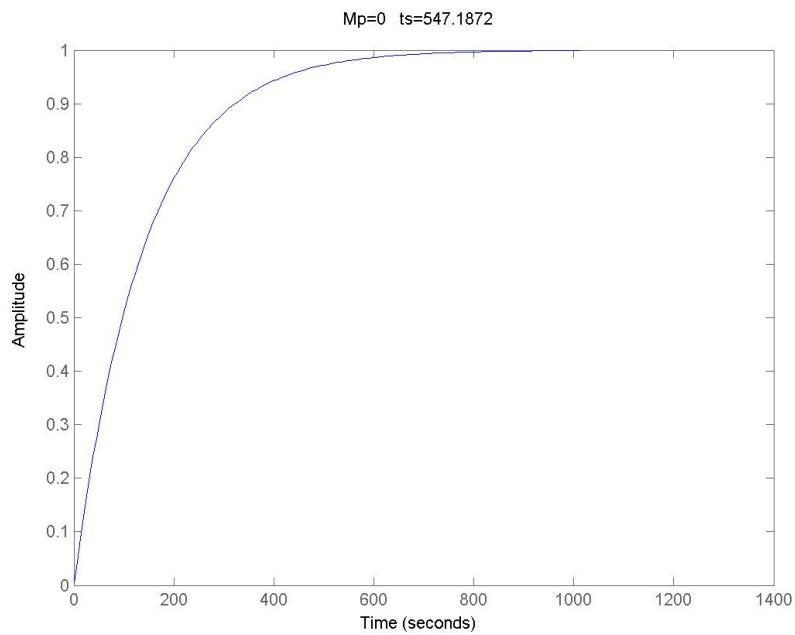


Figura 83: Resposta do sistema ao degrau unitário sem compensação

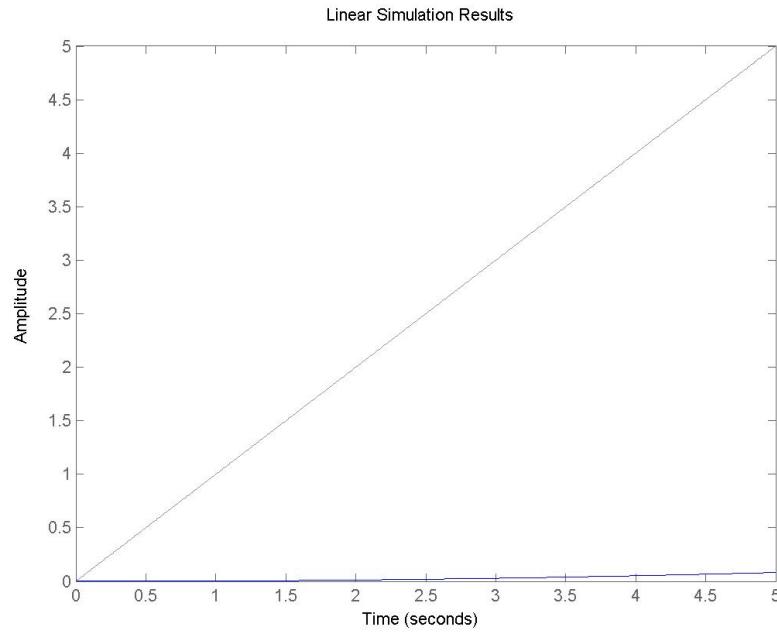


Figura 84: Resposta do sistema a rampa unitária sem compensação

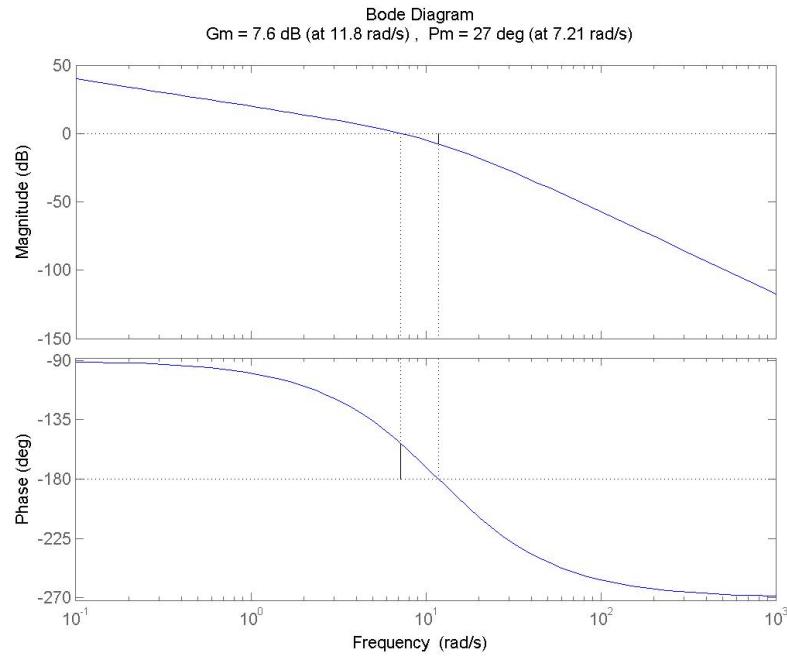


Figura 85: Diagrama de Bode do sistema com ajuste de ganho

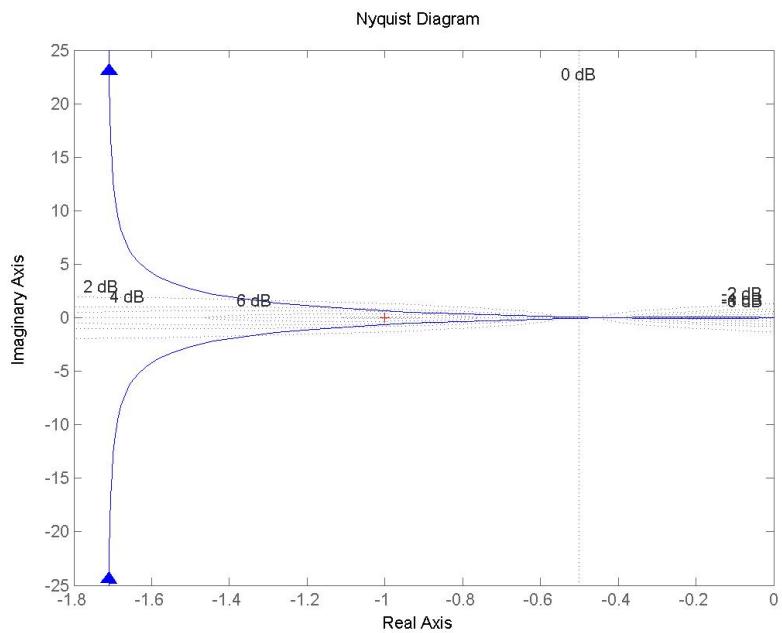


Figura 86: Diagrama de Nyquist do sistema com ajuste de ganho

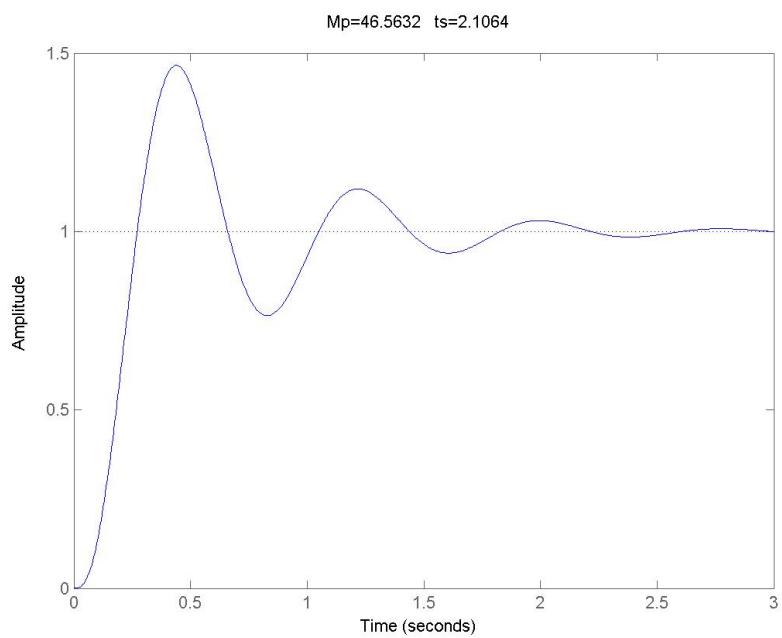


Figura 87: Resposta do sistema ao degrau unitário com ajuste de ganho

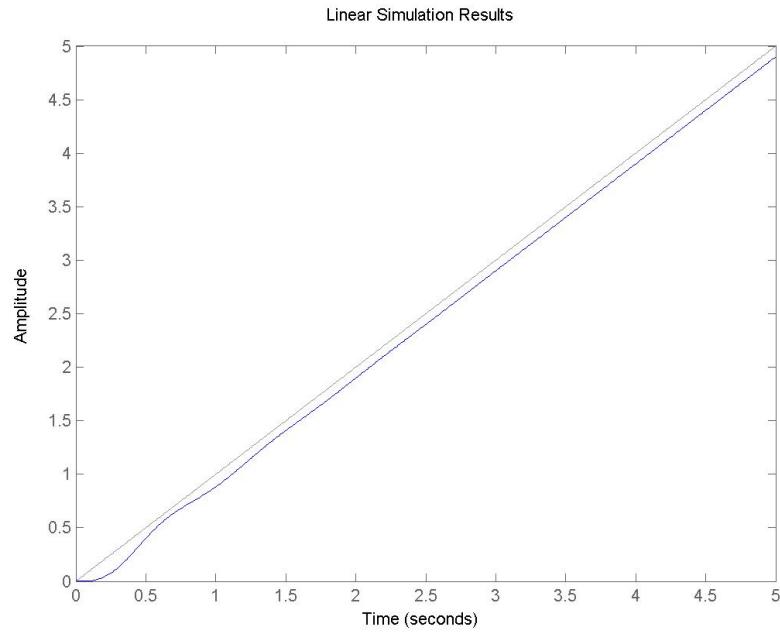


Figura 88: Resposta do sistema a rampa unitária com ajuste de ganho

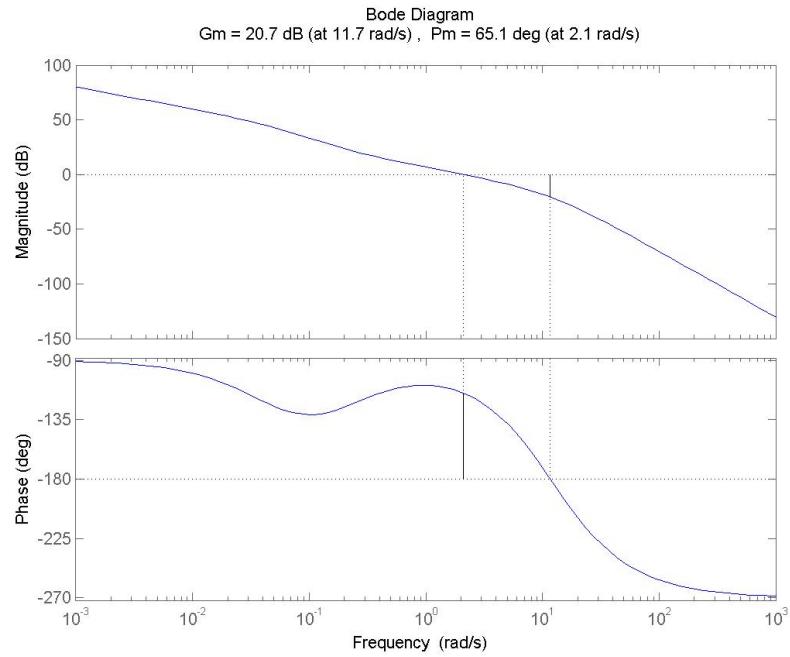


Figura 89: Diagrama de Bode do sistema com avanço de fase

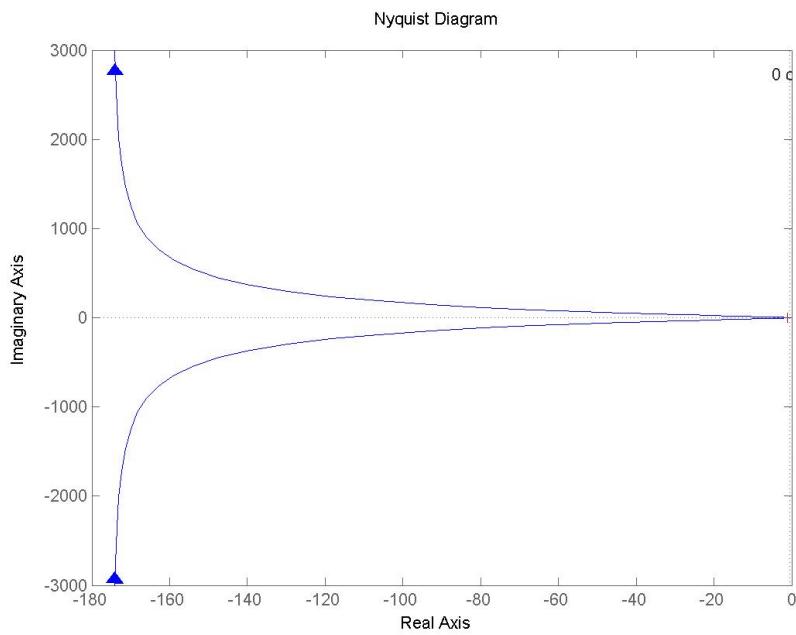


Figura 90: Diagrama de Nyquist do sistema com avanço de fase

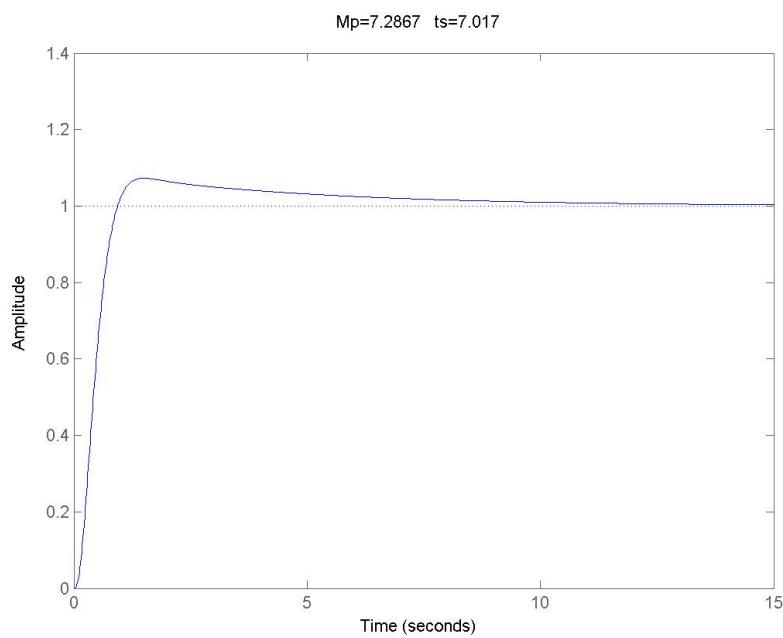


Figura 91: Resposta do sistema ao degrau unitário compensado por avanço

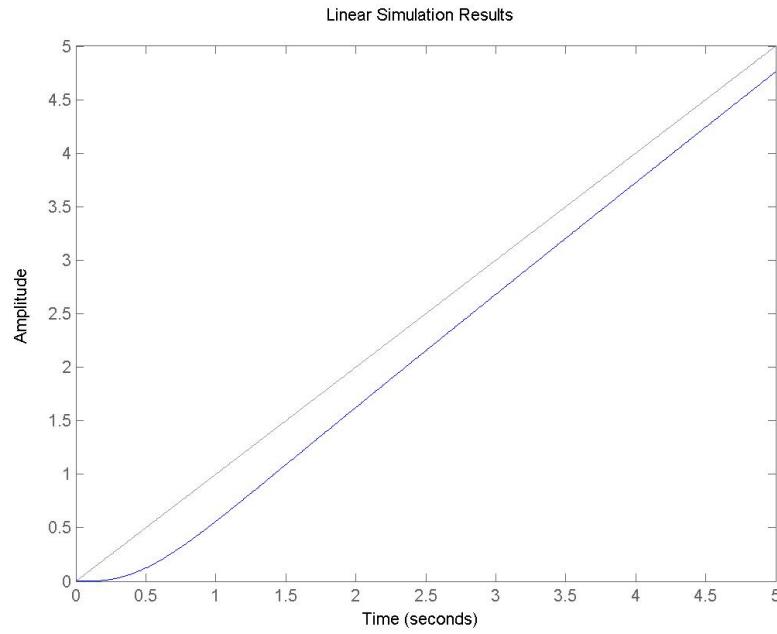


Figura 92: Resposta do sistema a rampa unitária compensado por avanço

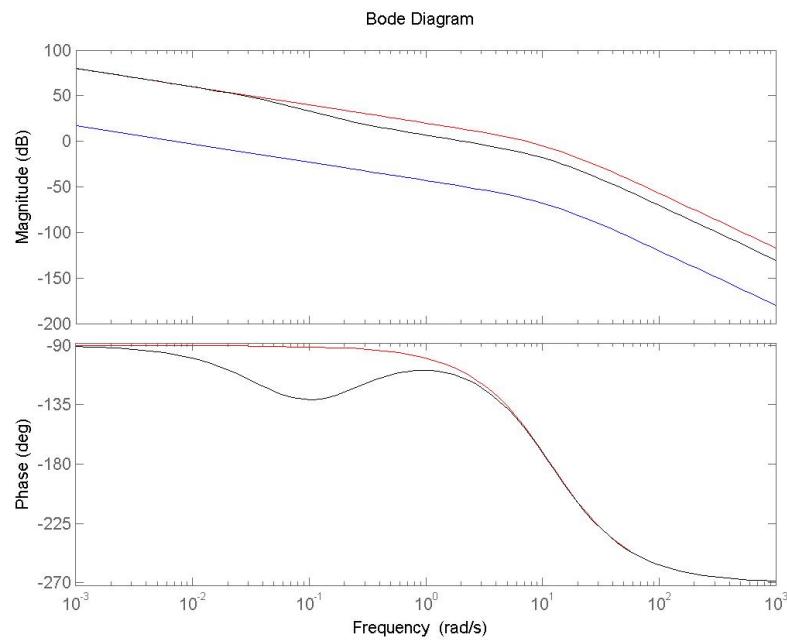


Figura 93: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

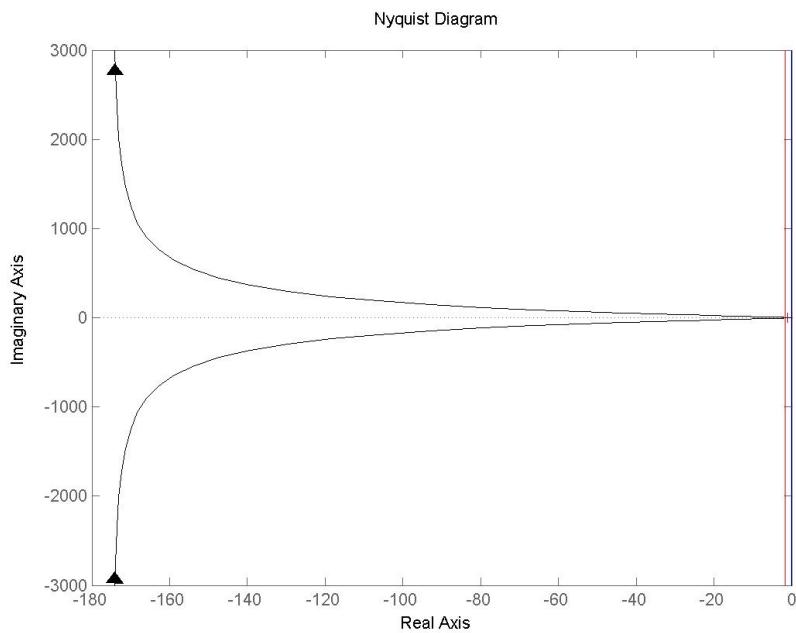


Figura 94: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

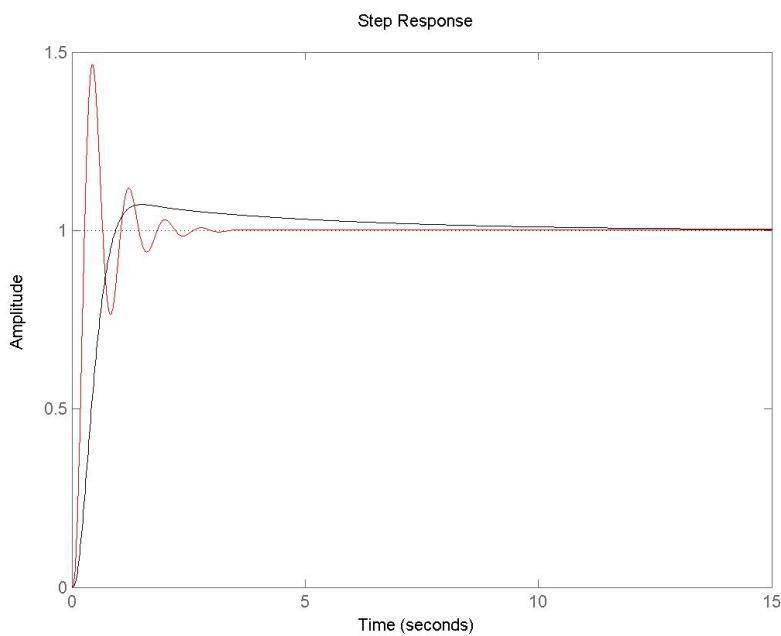


Figura 95: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

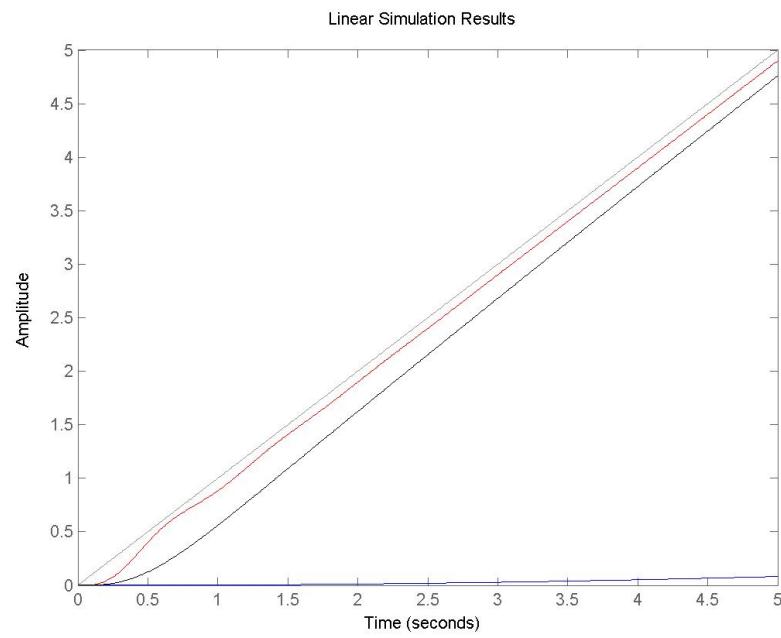


Figura 96: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

7 Exercício

$$G(s) = \frac{10e^{sT}}{s^2(s+10)}$$

$$\begin{cases} T = & 50ms = 0,05 \\ M_r \leq & 3,5dB \\ \omega_r = & 1,4rad/s \end{cases}$$

$$e^{-sT} = \frac{-s+40}{s+40}$$

$$G(s) = \frac{10(-s+40)}{s^2(s+10)(s+40)}$$

7.1 Margem de fase

$$M_r = \frac{1}{2\xi\sqrt{1-\xi^2}} \Rightarrow \sqrt{\xi^2 - \xi^4} = \frac{1}{2M_r} \Rightarrow \xi^4 - \xi^2 + \frac{1}{4M_r^2} = 0$$

$$\xi^2 = \frac{1 - \sqrt{1 - \frac{1}{M_r^2}}}{2} \Rightarrow \xi = \sqrt{\frac{1 - \sqrt{1 - \frac{1}{M_r^2}}}{2}}$$

$$\xi = \sqrt{\frac{1 - \sqrt{1 - \frac{1}{3,5^2}}}{2}} \Rightarrow \begin{cases} \xi_1 = 0,9895 \\ \xi_2 = 0,1444 \end{cases}$$

$$M_f = \arctan \left(\frac{2\xi}{\sqrt{\sqrt{1+4\xi^4}-2\xi}} \right) \Rightarrow \begin{cases} M_{f1} \approx 76,08 \\ M_{fdesejada} \approx 16,42 \end{cases}$$

$$\begin{cases} M_{fatual} = -8,55^\circ \\ \omega_{cg} = 0,998rad/s \end{cases}$$

7.2 Ângulo de avanço

$$\phi_m = M_{fdesejada} - M_{fatual} + t_{olerância}$$

$$\phi_m = 16,43^\circ - (-8,55) + 5^\circ = 29,98^\circ$$

7.3 Fator de atenuação

$$\phi_m = \arcsin \frac{1 - \alpha}{1 + \alpha} \Rightarrow \sin \phi_m = \frac{1 - \alpha}{1 + \alpha} \Rightarrow \alpha = \frac{1 - \sin \alpha}{1 + \sin \alpha}$$

$$\alpha = \frac{1 - \sin 29,98}{1 + \sin 29,98} = 0,3336$$

$$-20 \log \left(\frac{1}{\sqrt{\alpha}} \right) = -20 \log \left(\frac{1}{\sqrt{0,3336}} \right) = -4,7671 dB$$

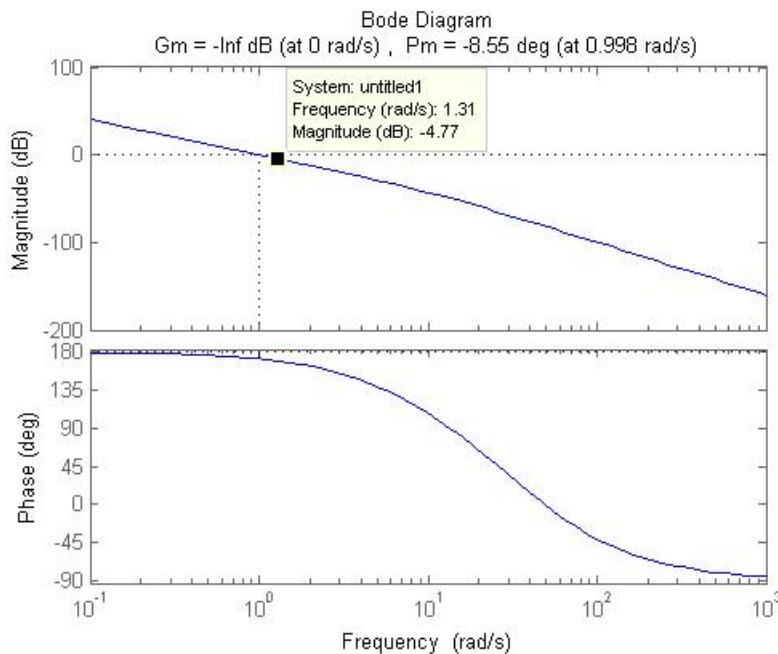


Figura 97: Frequência de defasagem máxima

$$\omega_m \approx 1.31 rad/s$$

7.4 Polos e zeros do compensador

$$\omega_m = \frac{1}{\sqrt{\alpha} T} \Rightarrow T = \frac{1}{\omega_m \sqrt{\alpha}}$$

$$T = \frac{1}{1,31 \sqrt{0,3336}} \cong 1,3216$$

$$\begin{cases} T = 1,3216 & (\text{zero}) \\ \alpha T = 0,4409 & (\text{polo}) \end{cases}$$

7.5 Compensador por avanço de fase

$$G_{av}(s)G(s) = \frac{Ts + 1}{\alpha Ts + 1} \frac{10(-s + 40)}{s^2(s + 10)(s + 40)}$$

$$G_{av}(s)G(s) = \frac{1,3216s + 1}{0,4409s + 1} \frac{10(-s + 40)}{s^2(s + 10)(s + 40)}$$

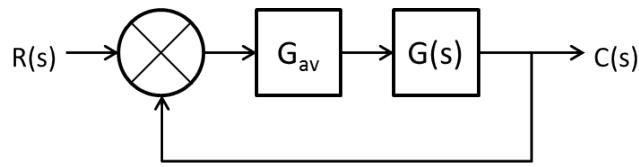


Figura 98: Diagrama de blocos do sistema compensado por avanço de fase

$$G_{av}(s)G(s) = \frac{-13s^2 + 518,6s + 400}{0,4409s^5 + 23,05s^4 + 226,4s^3 + 400s^2}$$

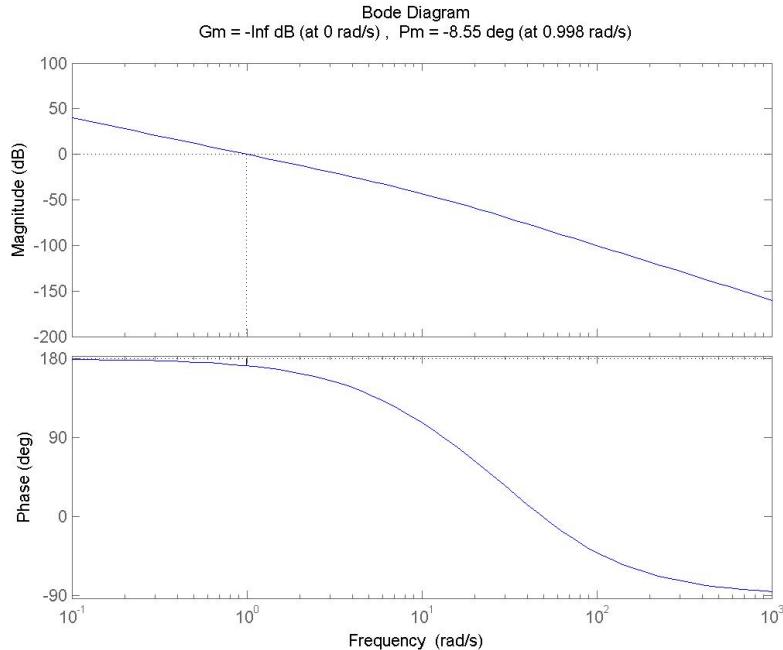


Figura 99: Diagrama de Bode do sistema sem compensação

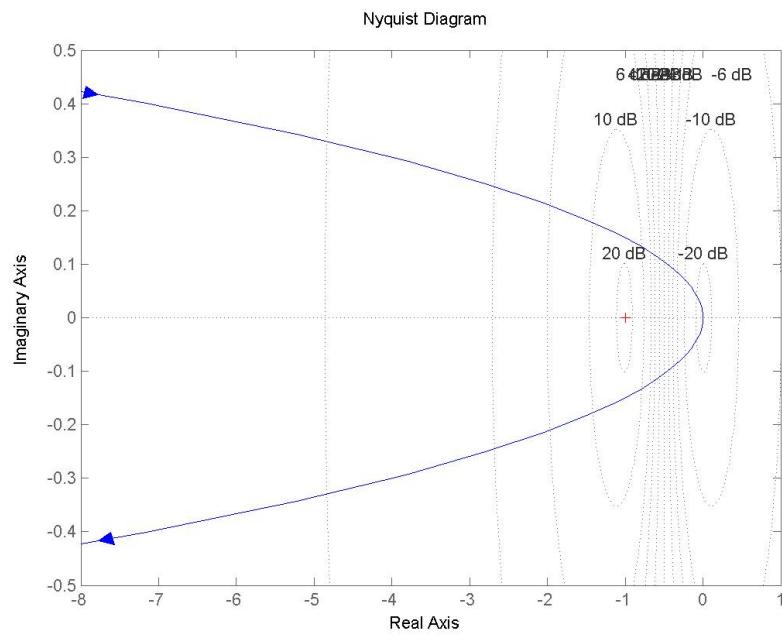


Figura 100: Diagrama de Nyquist do sistema sem compensação

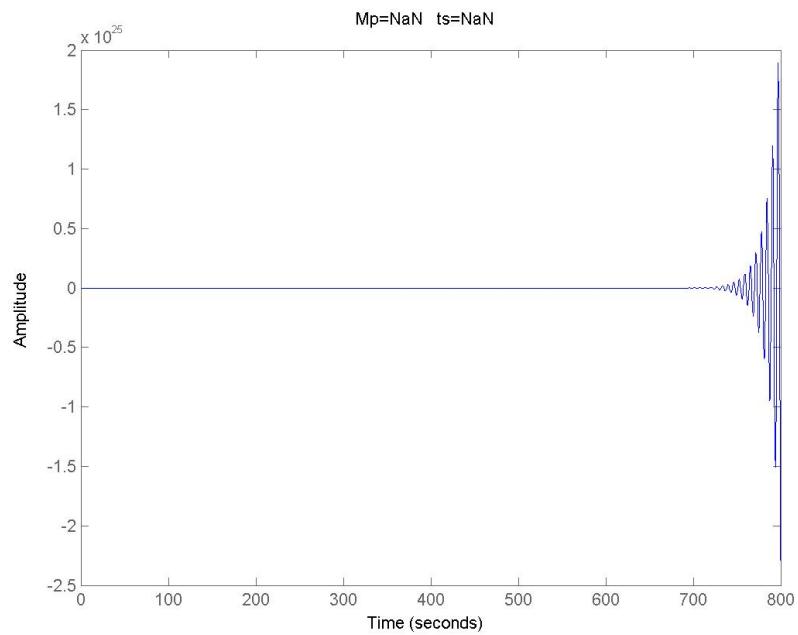


Figura 101: Resposta do sistema ao degrau unitário sem compensação

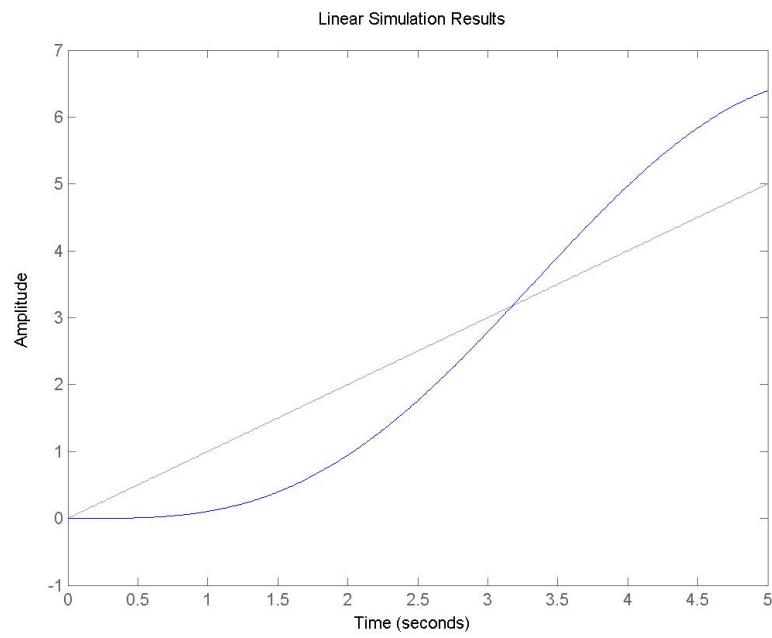


Figura 102: Resposta do sistema a rampa unitária sem compensação

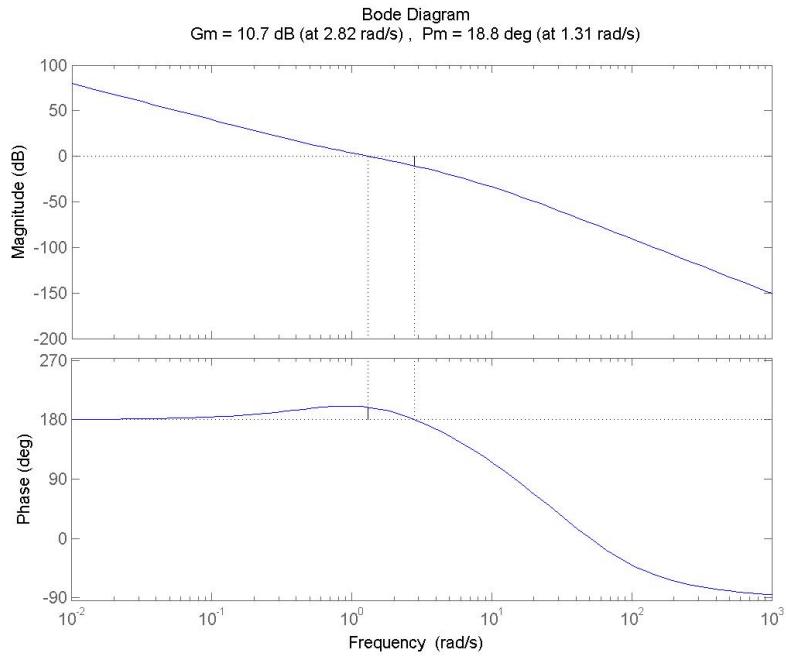


Figura 103: Diagrama de Bode do sistema com avanço de fase

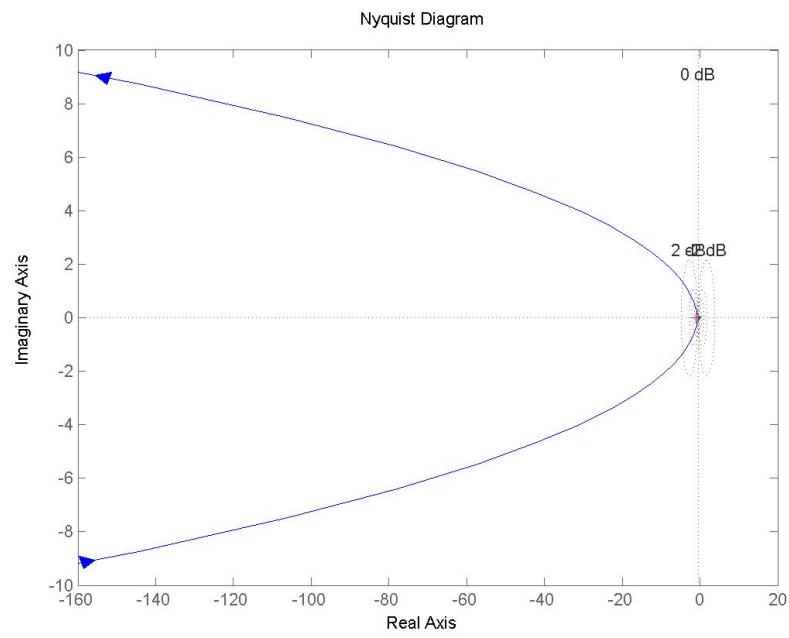


Figura 104: Diagrama de Nyquist do sistema com avanço de fase

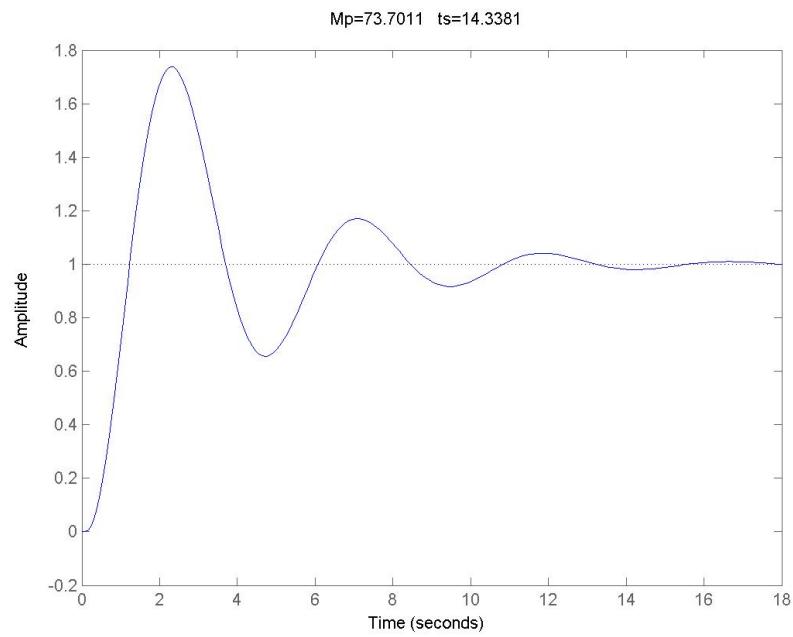


Figura 105: Resposta do sistema ao degrau unitário compensado por avanço

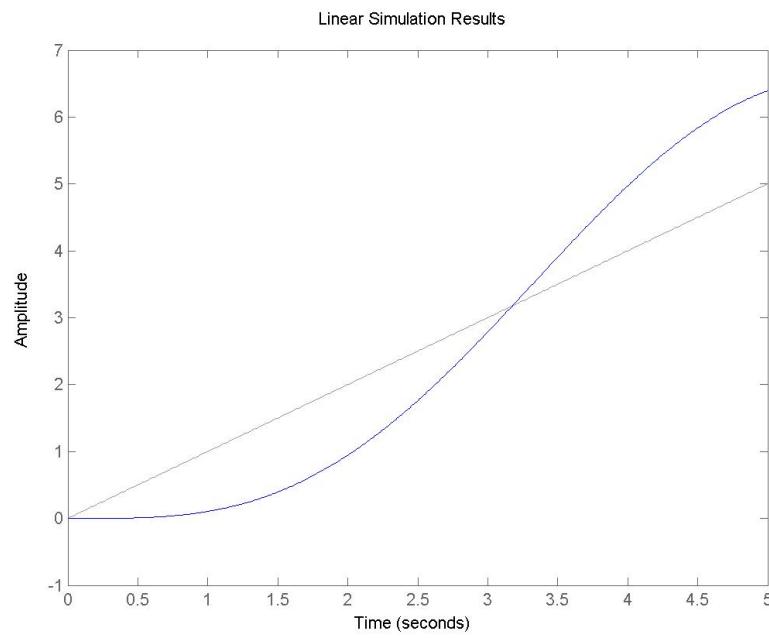


Figura 106: Resposta do sistema a rampa unitária compensado por avanço

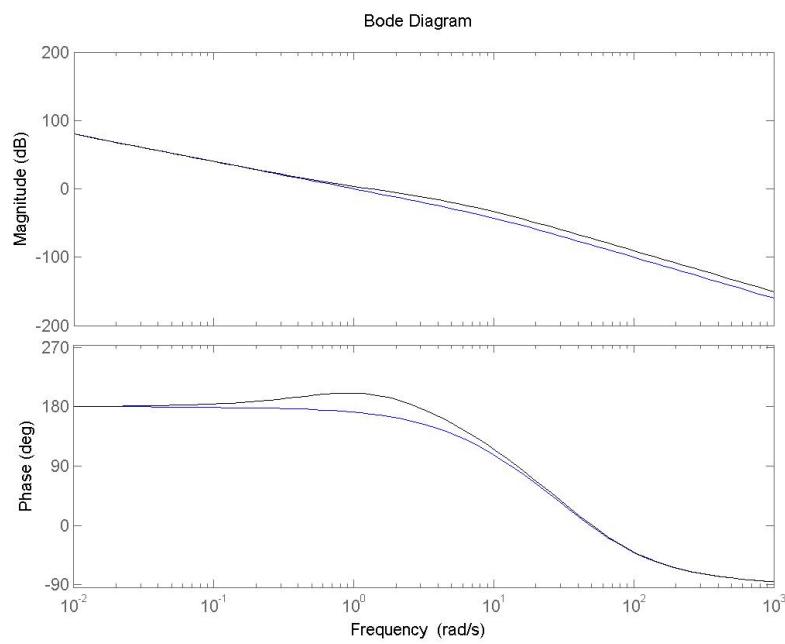


Figura 107: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

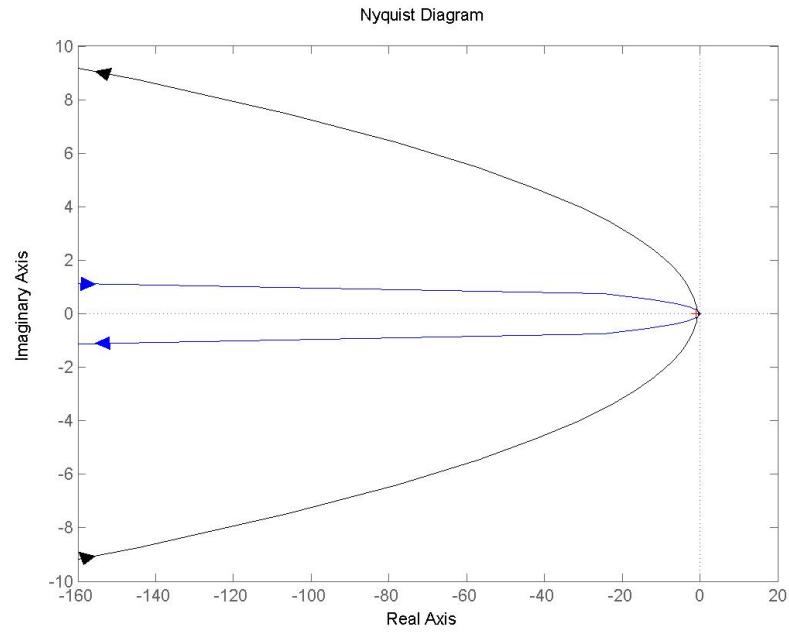


Figura 108: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

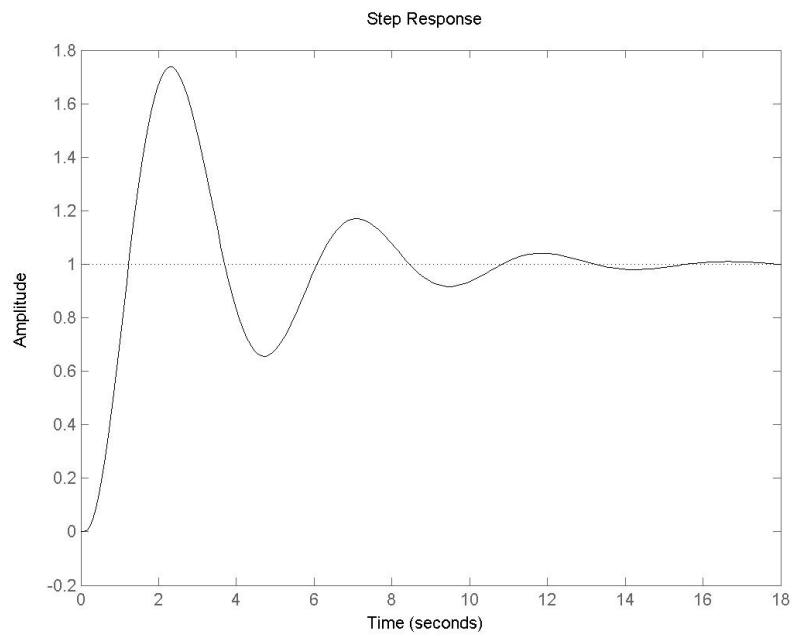


Figura 109: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

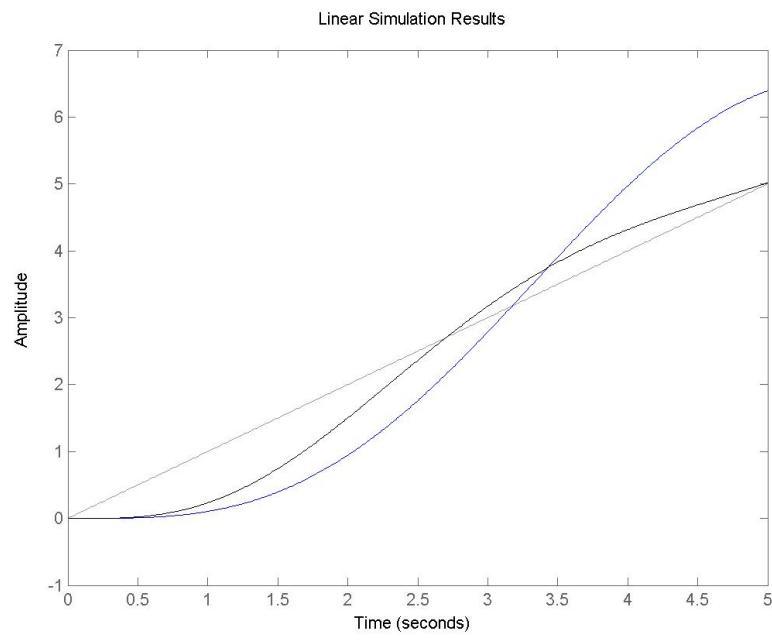


Figura 110: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

8 Exercício

$$G(s) = \frac{5}{0,1s+1} \frac{1}{s(0,001s+0,01)} 0,1 = \frac{50}{s(0,1s+1)^2}$$

$$\begin{cases} e_{ss} = 2,5\% = 0,025 \\ \xi_{desejada} = 0,7 \\ M_p \leq 0,05 = 5\% \end{cases}$$

8.1 Ajuste do ganho

$$K_v = \frac{1}{e_{ss}} = \lim_{s \rightarrow 0} s K_c G_{at}(s) G(s)$$

$$\frac{1}{0,025} = \lim_{s \rightarrow 0} s K_c \frac{Ts+1}{\beta Ts+1} \frac{50}{s(0,1s+1)^2}$$

$$40 = 0K_c \frac{T.0+1}{\beta T.0+1} \frac{50}{0(0,1.0+1)^2}$$

$$40 = 50K_c \Rightarrow \begin{cases} K_c = 0,8 \\ K_v = 40 \end{cases}$$

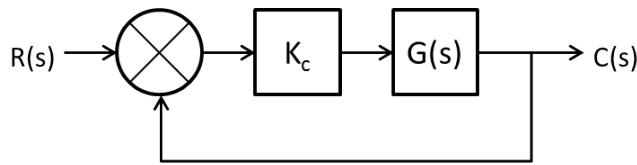


Figura 111: Diagrama de blocos do sistema com ganho ajustado

$$K_c G(s) = \frac{40}{s(0,1s+1)^2} \quad (2)$$

8.2 Margem de fase

$$M_{f_{desejada}} = \arctan \left(\frac{2\xi}{\sqrt{-2\xi^2 + \sqrt{1+4\xi^4}}} \right) = \arctan 2,1968 \cong 65^\circ$$

$$\begin{cases} M_{f_{atual}} = -18,1^\circ \\ \omega_{cg} = 13,8 rad/s \end{cases}$$

8.3 Ângulo de avanço

$$\phi_m = -180 + M_{f\text{desejada}} + t_{olerância}$$

$$\phi_m = -180^\circ + 65^\circ + 5^\circ = -110^\circ$$

8.4 Fator de atenuação

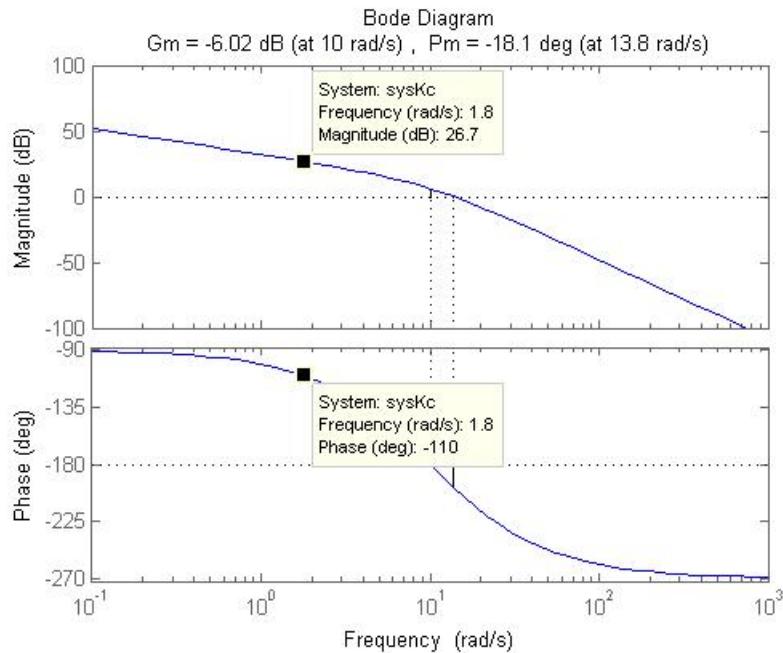


Figura 112: Frequência de defasagem máxima

$$\omega_m \approx 1,8 \text{ rad/s}$$

$$|G(s)|_{w=1,8} = 26,7 \text{ dB}$$

$$-20 \log \beta = -26,7 \Rightarrow \beta = 10^{26,7/20} = 21,6272$$

8.5 Polos e zeros do compensador

$$\omega_m = \frac{10}{T} \Rightarrow T \Rightarrow T = \frac{10}{\omega_m} = 5,5556$$

$$\begin{cases} T = 5,5556 & (\text{zero}) \\ \beta T = 120,2 & (\text{polo}) \end{cases}$$

8.6 Compensador por atraso de fase

$$K_c G_{at}(s) G(s) = K_c \frac{Ts + 1}{\beta Ts + 1} \frac{50}{s(0, 1s + 1)^2}$$

$$K_c G_{at}(s) G(s) = \frac{5,5556s + 1}{120,2s + 1} \frac{40}{s(0, 1s + 1)^2}$$

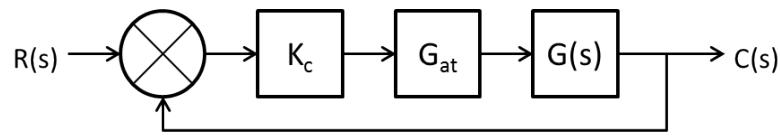


Figura 113: Diagrama de blocos do sistema compensado por atraso de fase

$$K_c G_{av}(s) G(s) = \frac{2,222s + 0,4}{0,01202s^4 + 0,2404s^3 + 1,204s^2 + 0,01s}$$

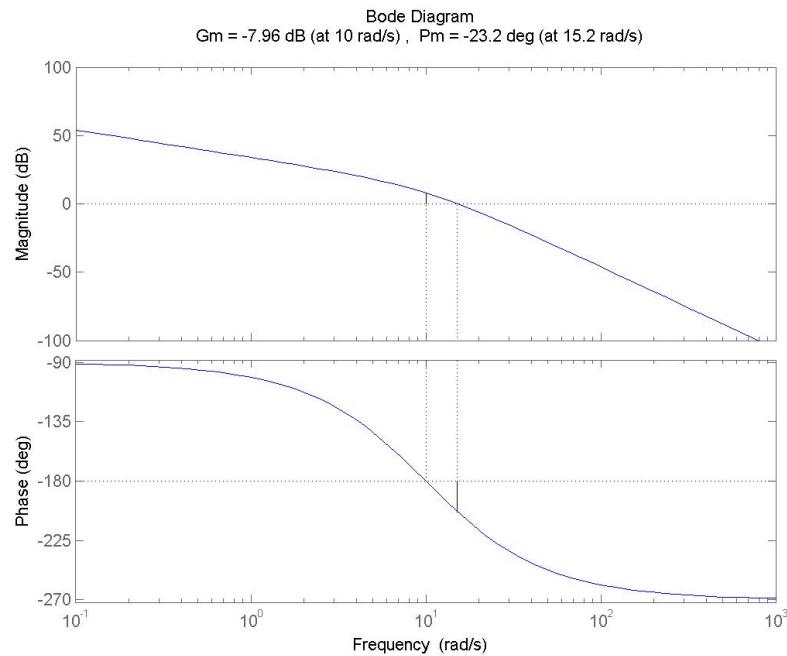


Figura 114: Diagrama de Bode do sistema sem compensação

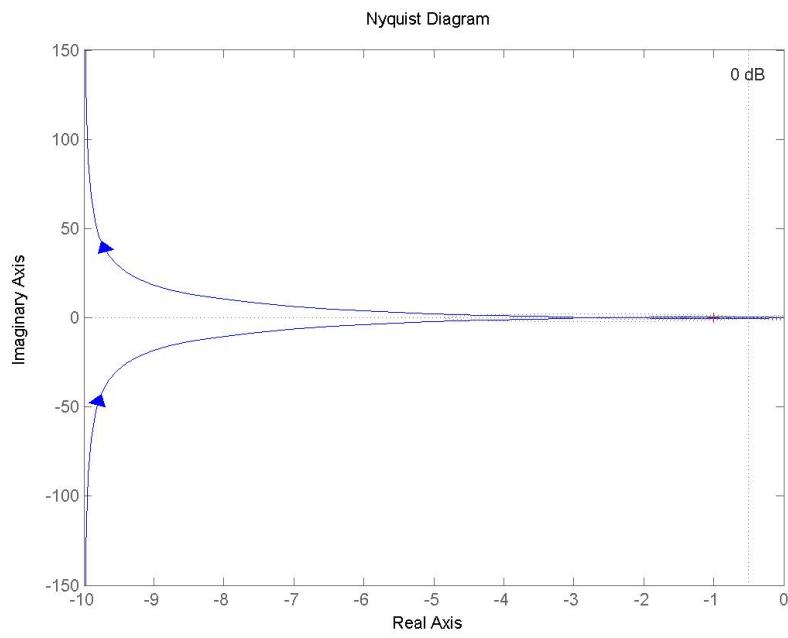


Figura 115: Diagrama de Nyquist do sistema sem compensação

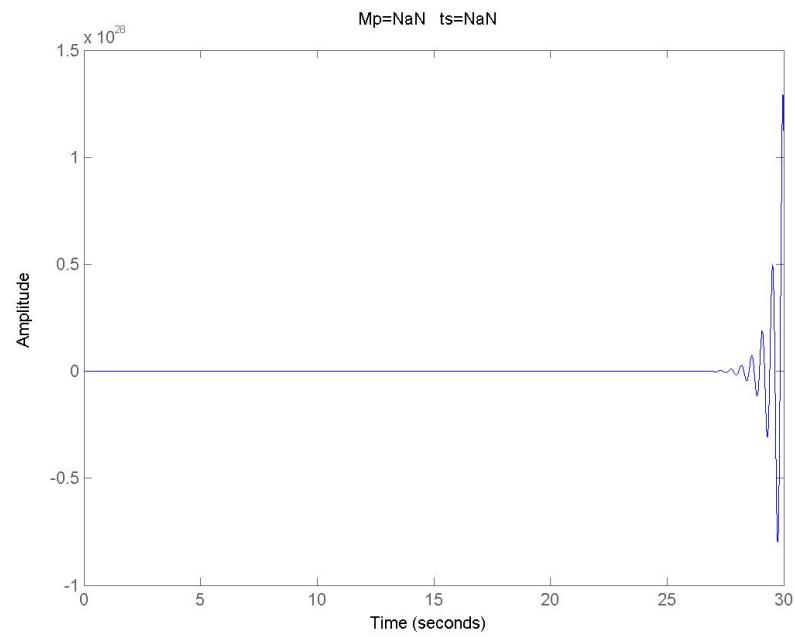


Figura 116: Resposta do sistema ao degrau unitário sem compensação

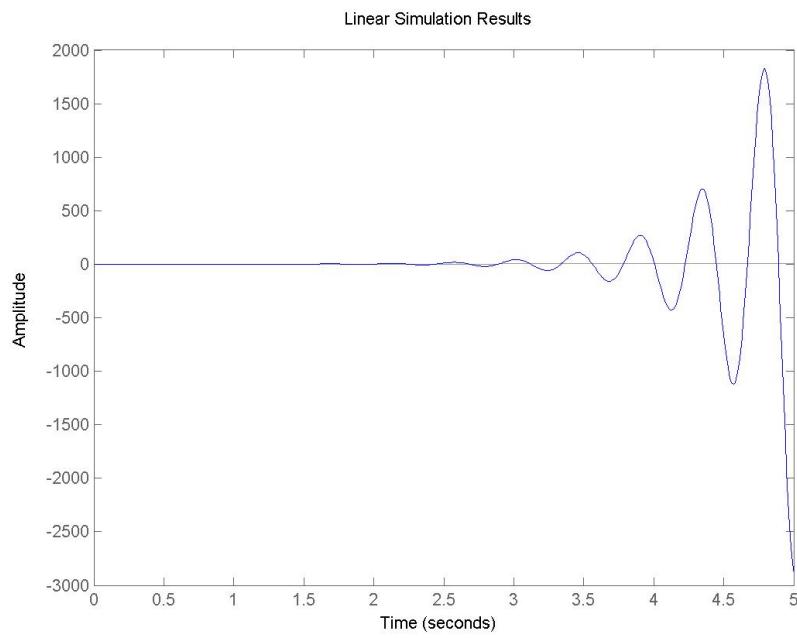


Figura 117: Resposta do sistema a rampa unitária sem compensação

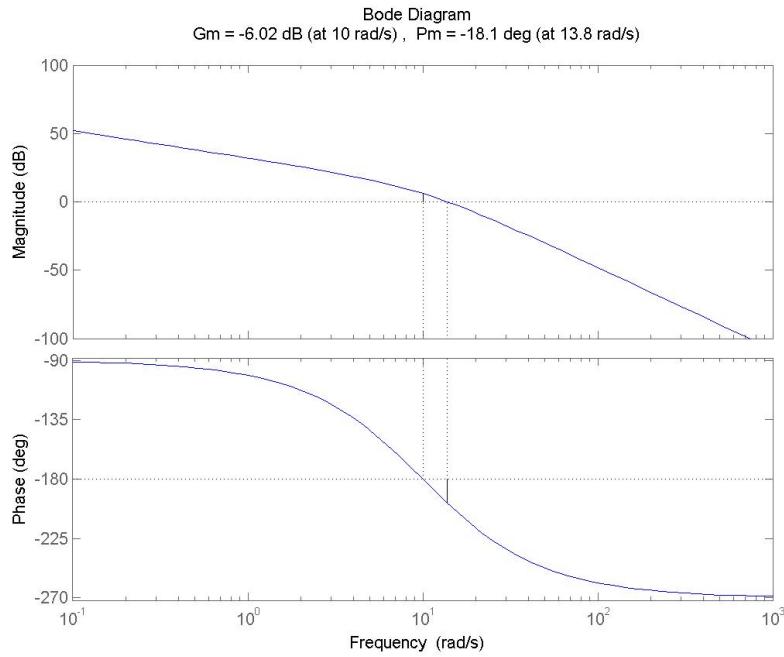


Figura 118: Diagrama de Bode do sistema com ajuste de ganho

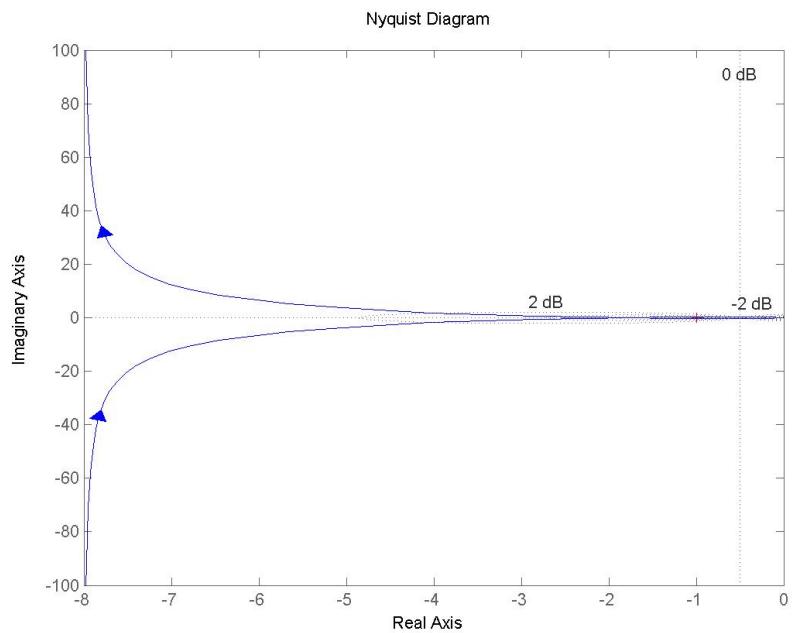


Figura 119: Diagrama de Nyquist do sistema com ajuste de ganho

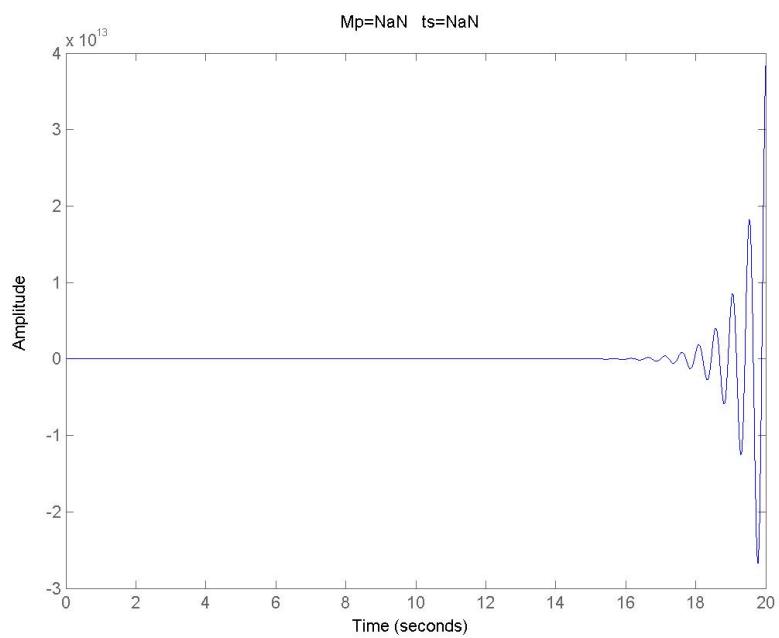


Figura 120: Resposta do sistema ao degrau unitário com ajuste de ganho

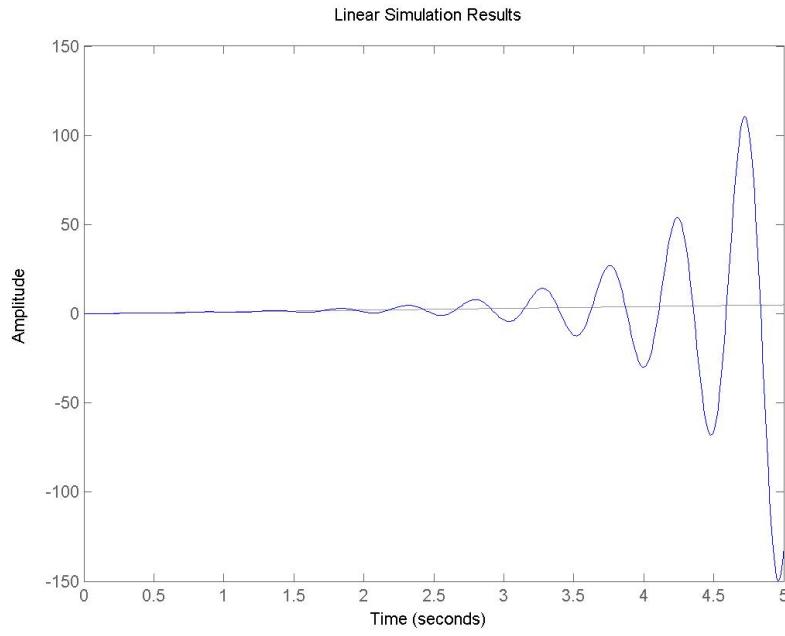


Figura 121: Resposta do sistema a rampa unitária com ajuste de ganho

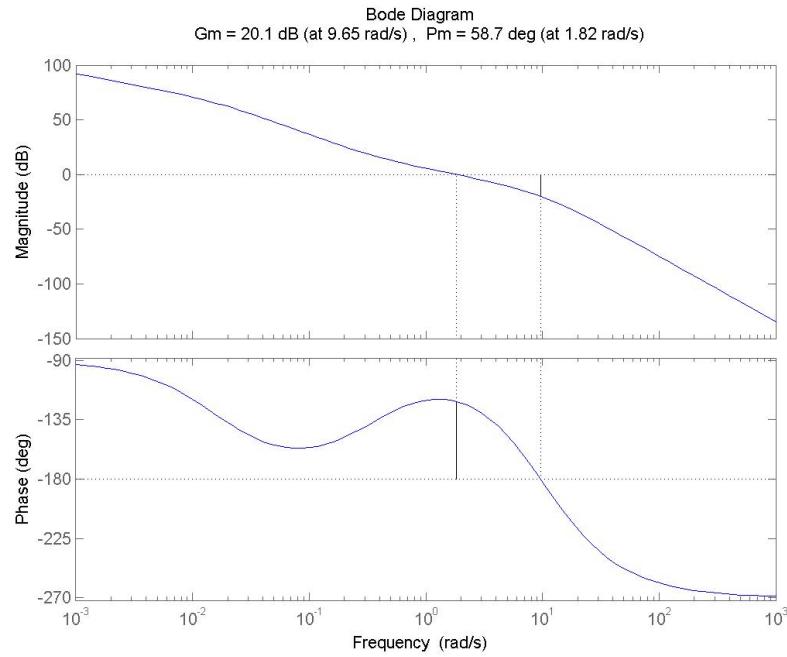


Figura 122: Diagrama de Bode do sistema com avanço de fase

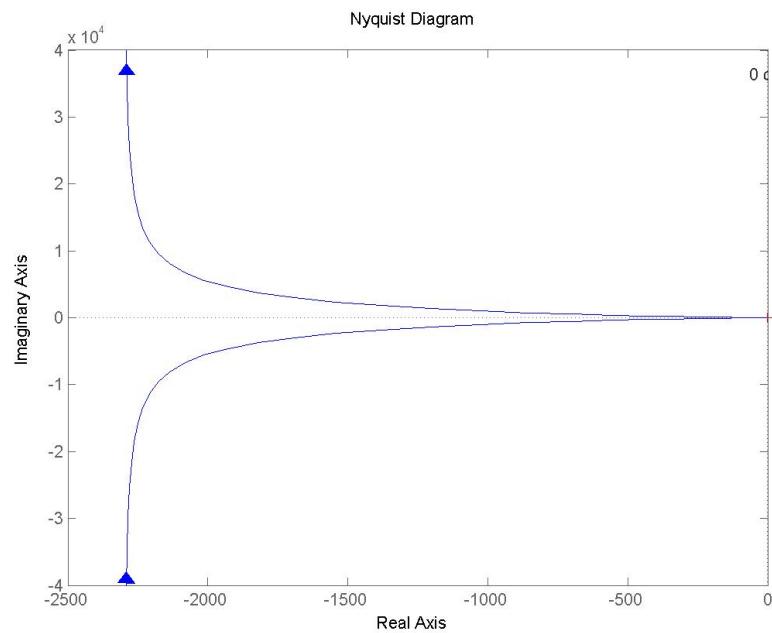


Figura 123: Diagrama de Nyquist do sistema com avanço de fase

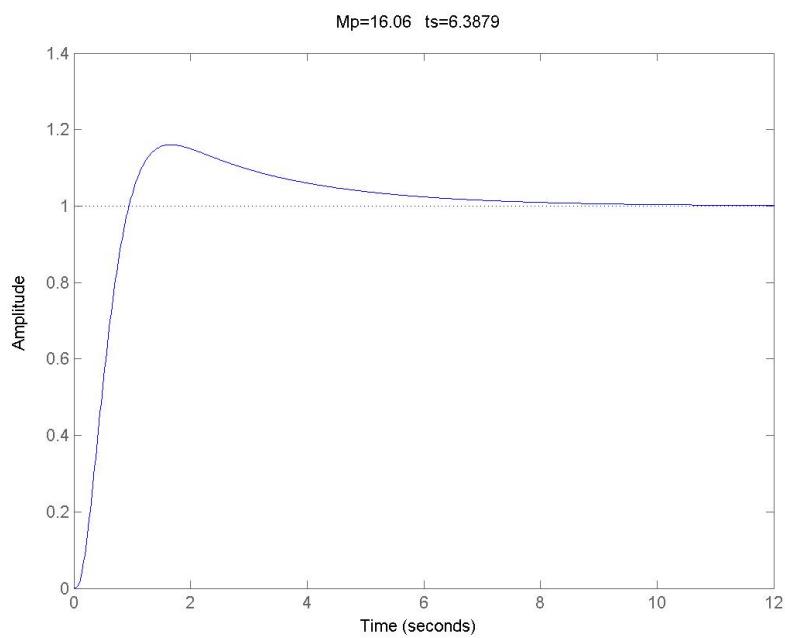


Figura 124: Resposta do sistema ao degrau unitário compensado por avanço

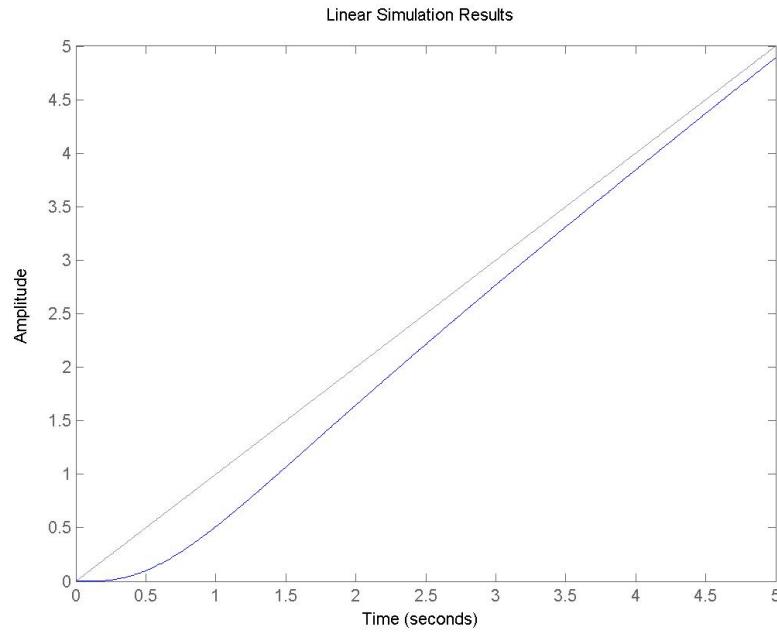


Figura 125: Resposta do sistema a rampa unitária compensado por avanço

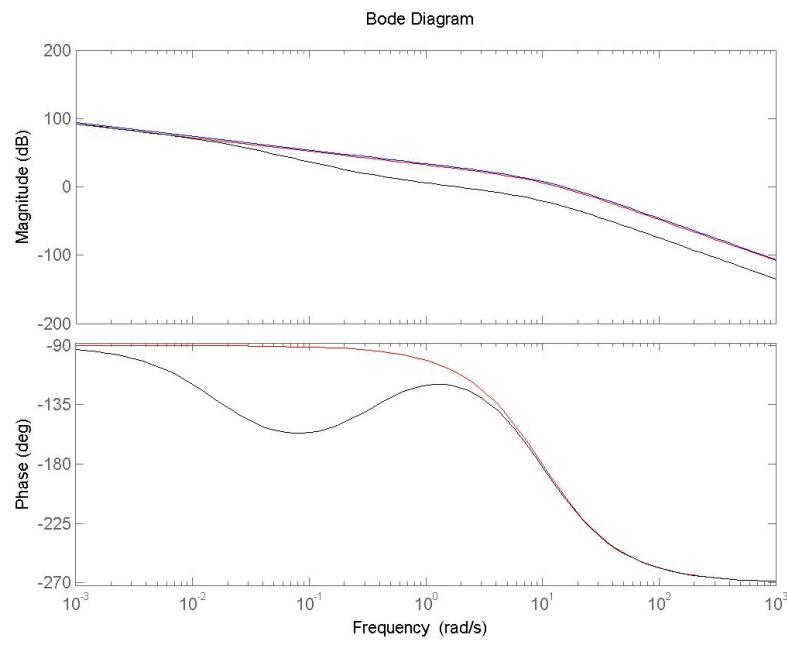


Figura 126: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

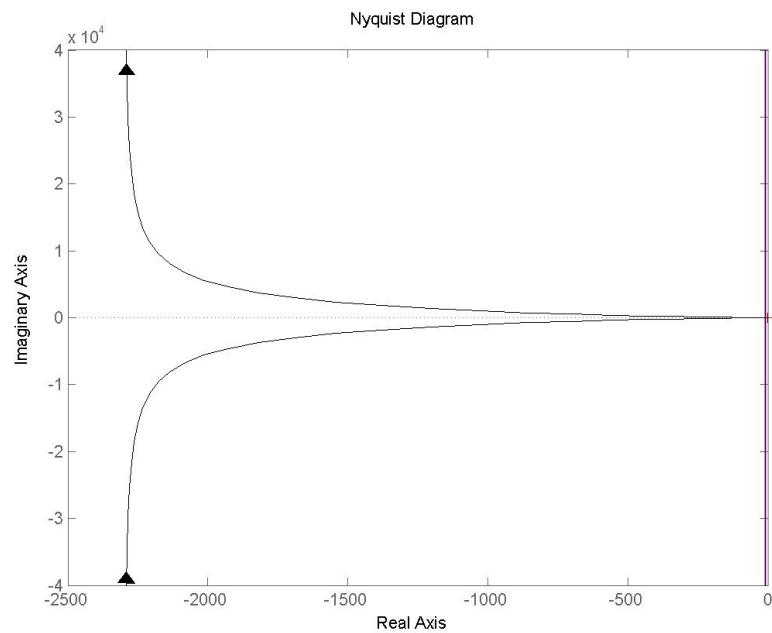


Figura 127: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

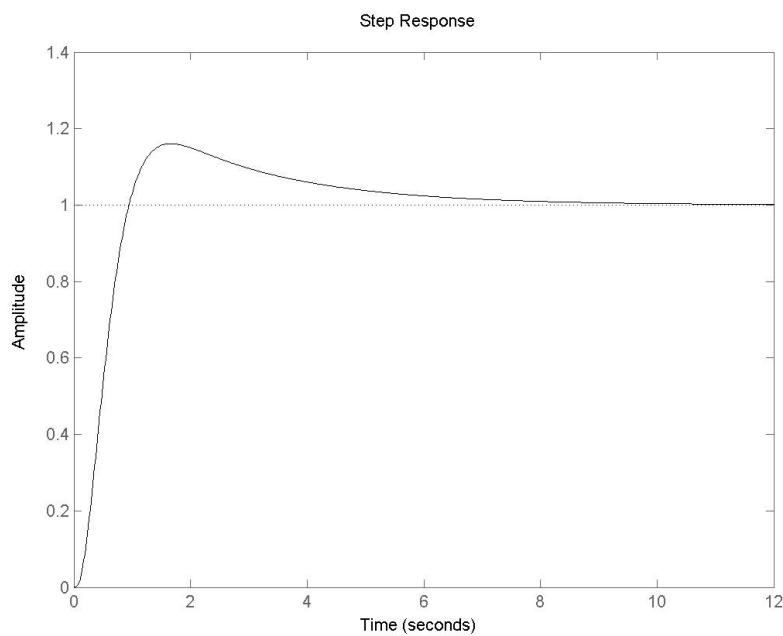


Figura 128: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

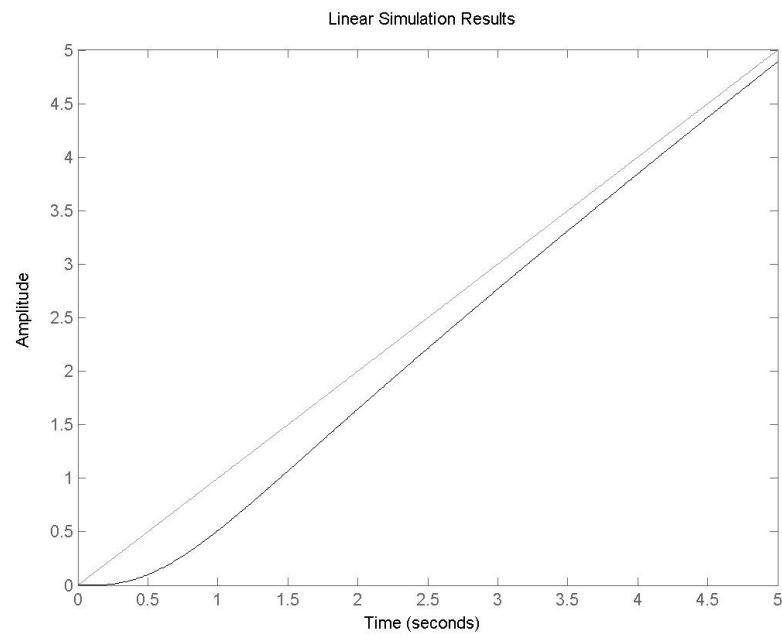


Figura 129: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

9 Exercício

9.1

$$D(s) = \frac{Ts + 1}{\alpha Ts + 1}$$

$$\phi = \angle(Tj\omega + 1) - \angle(\alpha Tj\omega + 1)$$

$$\phi = \arctan \left[\frac{T\omega}{1} \right] - \arctan \left[\frac{\alpha T\omega}{1} \right]$$

9.2

$$\phi_{max} \Leftarrow \phi' = 0$$

$$y = \arctan u(x) \Rightarrow y' = \frac{u'(x)}{1 + u^2(x)}$$

$$\phi' = \left[\frac{T}{1 + (T\omega)^2} \right] - \left[\frac{\alpha T}{1 + (\alpha T\omega)^2} \right] = 0$$

$$\left[\frac{T}{1 + (T\omega)^2} \right] = \left[\frac{\alpha T}{1 + (\alpha T\omega)^2} \right]$$

$$T(1 + (\alpha T\omega)^2) = \alpha T(1 + (T\omega)^2)$$

$$\omega^2(\alpha^2 T^3 - \alpha T^3) = T(\alpha - 1)$$

$$\omega^2 \alpha T^3 (\alpha - 1) = T(\alpha - 1)$$

$$\omega^2 = \frac{1}{\alpha T^2}$$

$$\omega_{max} = \frac{1}{\sqrt{\alpha} T}$$

$$\phi_{max} = \arctan(\omega_{max} T) - \arctan(\alpha \omega_{max} T)$$

$$\phi_{max} = \arctan \left(\frac{1}{\sqrt{\alpha} T} T \right) - \arctan \left(\frac{1}{\sqrt{\alpha} T} \alpha T \right)$$

$$\phi_{max} = \arctan \left(\frac{1}{\sqrt{\alpha}} \right) - \arctan \left(\frac{\alpha}{\sqrt{\alpha}} \right)$$

$$\begin{cases} \sin\left(\arctan\left(\frac{1}{\sqrt{\alpha}}\right)\right) = \frac{1}{\sqrt{\alpha+1}} \\ \cos\left(\arctan\left(\frac{1}{\sqrt{\alpha}}\right)\right) = \frac{1}{\sqrt{1+\frac{1}{\alpha}}} \\ \sin\left(\arctan\left(\frac{\alpha}{\sqrt{\alpha}}\right)\right) = \frac{\sqrt{\alpha}}{\sqrt{\alpha+1}} \\ \cos\left(\arctan\left(\frac{\alpha}{\sqrt{\alpha}}\right)\right) = \frac{1}{\sqrt{\alpha+1}} \end{cases}$$

$$\sin(a - b) = \sin a \cos b - \sin b \cos a$$

$$\sin \phi_{max} = \sin \left[\arctan\left(\frac{1}{\sqrt{\alpha}}\right) - \arctan\left(\frac{\alpha}{\sqrt{\alpha}}\right) \right]$$

$$\begin{aligned} \sin \phi_{max} &= \sin\left(\arctan\left(\frac{1}{\sqrt{\alpha}}\right)\right) \cos\left(\arctan\left(\frac{\alpha}{\sqrt{\alpha}}\right)\right) \\ &\quad - \sin\left(\arctan\left(\frac{\alpha}{\sqrt{\alpha}}\right)\right) \cos\left(\arctan\left(\frac{1}{\sqrt{\alpha}}\right)\right) \end{aligned}$$

$$\sin \phi_{max} = \frac{1}{\sqrt{\alpha+1}} \frac{1}{\sqrt{\alpha+1}} - \frac{\sqrt{\alpha}}{\sqrt{\alpha+1}} \frac{1}{\sqrt{1+\frac{1}{\alpha}}}$$

$$\sin \phi_{max} = \frac{1}{\alpha+1} - \frac{\sqrt{\alpha}}{\sqrt{\alpha + \frac{\alpha}{\alpha} + 1 + \frac{1}{\alpha}}}$$

$$\sin \phi_{max} = \frac{1}{\alpha+1} - \frac{\sqrt{\alpha}}{\sqrt{\frac{\alpha^2+2\alpha+1}{\alpha}}}$$

$$\sin \phi_{max} = \frac{1}{\alpha+1} - \frac{\sqrt{\alpha}}{\frac{\sqrt{(\alpha+1)^2}}{\sqrt{\alpha}}}$$

$$\sin \phi_{max} = \frac{1}{\alpha+1} - \frac{\sqrt{\alpha}\sqrt{\alpha}}{\alpha+1}$$

$$\sin \phi_{max} = \frac{1-\alpha}{1+\alpha}$$

9.3

$$\log(\omega_{max}) = \log\left(\frac{1}{\sqrt{\alpha T}}\right)$$

$$\log(\omega_{max}) = \log 1 - \log \sqrt{\alpha} - \log T$$

$$\log(\omega_{max}) = -\log T - \frac{\log \alpha}{2}$$

$$\log(\omega_{max}) = -\frac{2 \log T}{2} - \frac{\log \alpha}{2}$$

$$\log(\omega_{max}) = \frac{1}{2} [-2 \log T - \log \alpha]$$

$$\log(\omega_{max}) = \frac{1}{2} [-\log T - \log T - \log \alpha]$$

$$\log(\omega_{max}) = \frac{1}{2} [0 - \log T + 0 - \log T - \log \alpha]$$

$$\log(\omega_{max}) = \frac{1}{2} [\log 1 - \log T + \log 1 - \log \alpha - \log T]$$

$$\log(\omega_{max}) = \frac{1}{2} \left[\log \frac{1}{T} + \log \frac{1}{\alpha T} \right]$$

9.4

$$D(s) = \frac{s+Z}{\alpha(s+P)} \text{ onde } \begin{cases} Z = & \frac{1}{T} \\ P = & \frac{1}{\alpha T} \end{cases}$$

$$\phi = \angle \left(s + \frac{1}{T} \right) - \angle \alpha - \angle \left(s + \frac{1}{\alpha T} \right)$$

$$\phi = \arctan(\omega T) - \arctan(\omega \alpha T)$$

$$\phi = \arctan \left(\frac{\omega}{Z} \right) - \arctan \left(\frac{\omega}{P} \right)$$

$$\omega_{max} = \frac{1}{\sqrt{\alpha T}} = \sqrt{\frac{1}{\alpha T^2}} = \sqrt{\frac{1}{T} \frac{1}{\alpha T}} = \sqrt{Z.P}$$

10 Exercício

$$G(s) = \frac{0,5}{s(s+1)(0,5s+1)}$$

$$\begin{cases} Kp = 9 \\ M_{f\text{desejada}} \geq 25^\circ \end{cases}$$

10.1 Ajuste do ganho

$$K_v = \frac{1}{e_{ss}} = \lim_{s \rightarrow 0} s K_c G_{av}(s) G(s)$$

$$\frac{1}{0,1} = \lim_{s \rightarrow 0} s K_c \frac{T_1 s + 1}{\alpha T_1 s + 1} \frac{0,5}{s(s+1)(0,5s+1)}$$

$$10 = 0K_c \frac{T_1 \cdot 0 + 1}{\alpha T_1 \cdot 0 + 1} \frac{0,5}{0(0+1)(0,5 \cdot 0 + 1)}$$

$$10 = 0,5Kc \Rightarrow \begin{cases} K_c = 20 \\ K_v = 10 \end{cases}$$

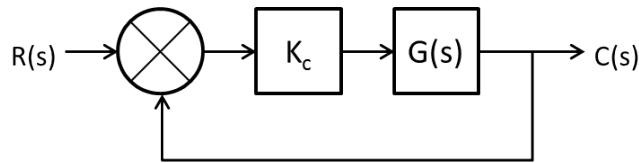


Figura 130: Diagrama de blocos do sistema com ganho ajustado

$$G(s) = \frac{10}{s(s+1)(0,5s+1)}$$

$$\begin{cases} M_{fatual} = -28,1^\circ \\ \omega_{cg} = 2,43 \text{ rad/s} \end{cases}$$

10.2 Ângulo de avanço

$$\phi_m = 25^\circ$$

10.3 Fator de atenuação

$$\phi_m = \arcsin \frac{1 - \alpha_1}{1 + \alpha_1} \Rightarrow \sin \phi_m = \frac{1 - \alpha_1}{1 + \alpha_1} \Rightarrow \alpha_1 = \frac{1 - \sin \phi_m}{1 + \sin \phi_m}$$

$$\alpha_1 = \frac{1 - \sin 25}{1 + \sin 25} = 0,333$$

$$-20 \log \left(\frac{1}{\sqrt{\alpha_1}} \right) = -20 \log \left(\frac{1}{\sqrt{0,333}} \right) = -4,77dB$$

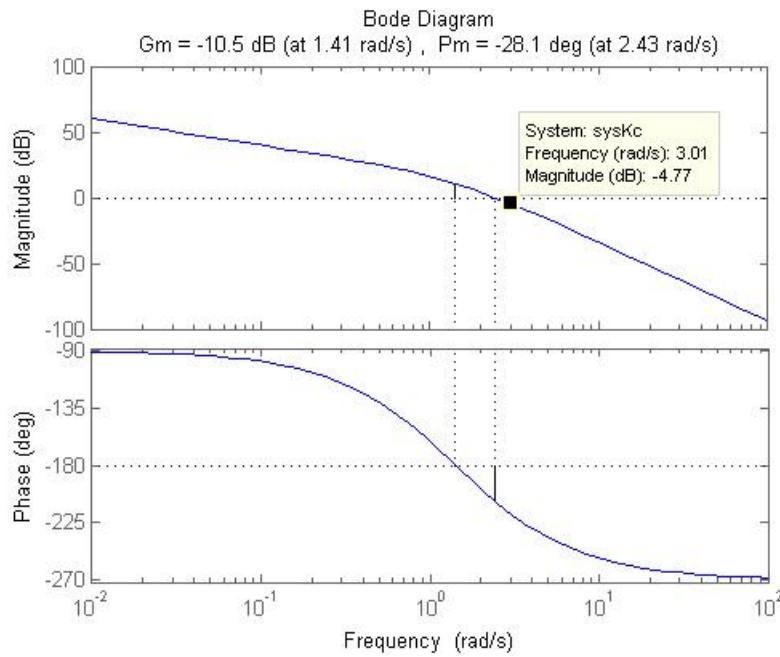


Figura 131: Frequência de defasagem máxima

$$\omega_m \approx 3rad/s$$

10.4 Polos e zeros do compensador

$$\omega_m = \frac{1}{\sqrt{\alpha_1} T_1} \Rightarrow T_1 = \frac{1}{\omega_m \sqrt{\alpha_1}}$$

$$T_1 = \frac{1}{3\sqrt{0,333}} \cong 0,5774$$

$$\begin{cases} T_1 = 0,5774 & (\text{zero}) \\ \alpha_1 T_1 = 0,1925 & (\text{polo}) \end{cases}$$

10.5 Compensador por avanço de fase

$$K_c G_{av}(s)G(s) = K_c \frac{Ts + 1}{\alpha Ts + 1} \frac{0,5}{s(s+1)(0,5s+1)}$$

$$K_c G_{av}(s)G(s) = 20 \frac{0,5774s + 1}{0,1925s + 1} \frac{0,5}{s(s+1)(0,5s+1)}$$

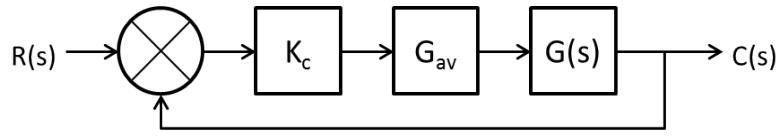


Figura 132: Diagrama de blocos do sistema controlado por avanço de fase

$$K_c G_{av}(s)G(s) = \frac{5,774s + 10}{0,06923s^4 + 0,7887s^3 + 1,692s^2 + s}$$

$$\begin{cases} M_{factual} = -8,14^\circ \\ \omega_{cg} = 3,02 \text{ rad/s} \end{cases}$$

10.6 Ângulo de avanço

$$\phi_m = M_{fdesejada} - M_{factual} + t_{olerância}$$

$$\phi_m = 25^\circ - (-8,14^\circ) + 12^\circ = 45^\circ$$

10.7 Fator de atenuação

$$\phi_m = \arcsin \frac{1 - \alpha_2}{1 + \alpha_2} \Rightarrow \sin \phi_m = \frac{1 - \alpha_2}{1 + \alpha_2} \Rightarrow \alpha_2 = \frac{1 - \sin \phi_m}{1 + \sin \phi_m}$$

$$\alpha_2 = \frac{1 - \sin 45}{1 + \sin 45} = 0,1704$$

$$-20 \log \left(\frac{1}{\sqrt{\alpha_2}} \right) = -20 \log \left(\frac{1}{\sqrt{0,1704}} \right) = -7,6856 \text{ dB}$$

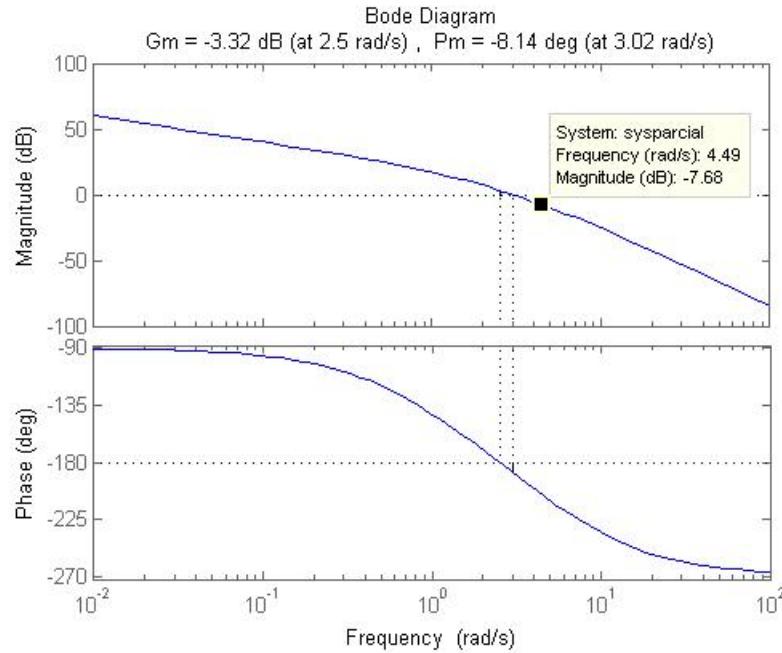


Figura 133: Frequênciade defasagem máxima

$$\omega_m \approx 4,49 \text{ rad/s}$$

10.8 Polos e zeros do compensador

$$\omega_m = \frac{1}{\sqrt{\alpha_2} T_2} \Rightarrow T_2 = \frac{1}{\omega_m \sqrt{\alpha_2}}$$

$$T_2 = \frac{1}{4,49 \sqrt{0,1704}} \cong 0,5396$$

$$\begin{cases} T_2 = 0,5396 \text{ (zero)} \\ \alpha_2 T_2 = 0,09193 \text{ (polo)} \end{cases}$$

10.9 Compensador por avanço-avanço de fase

$$K_c G_{av}(s) G(s) = K_c \frac{T_1 s + 1}{\alpha_1 T_1 s + 1} \frac{T_2 s + 1}{\alpha_2 T_2 s + 1} \frac{0,5}{s(s+1)(0,5s+1)}$$

$$K_c G_{av}(s) G(s) = 20 \frac{0,5774s + 1}{0,1925s + 1} \frac{0,5396s + 1}{0,09193s + 1} \frac{0,5}{s(s+1)(0,5s+1)}$$

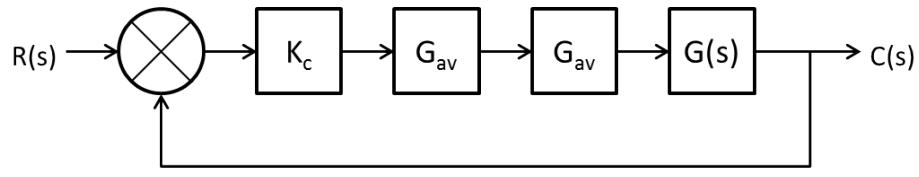


Figura 134: Diagrama de blocos do sistema controlado por avanço-avanço

$$K_c G_{av}(s) G(s) = \frac{3,115s^2 + 11,17s + 10}{0,008846s^5 + 0,1687s^4 + 0,9443s^3 + 1,784s^2 + s}$$

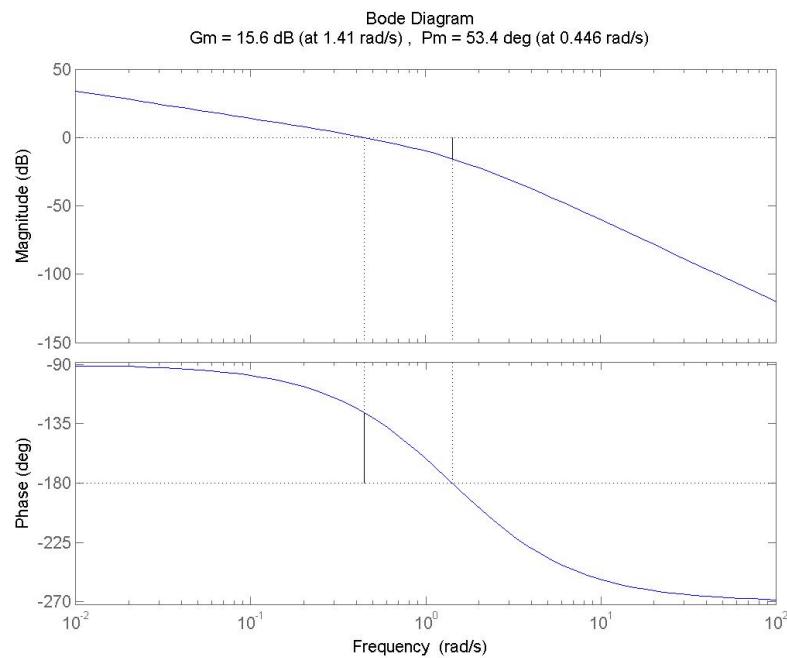


Figura 135: Diagrama de Bode do sistema sem compensação

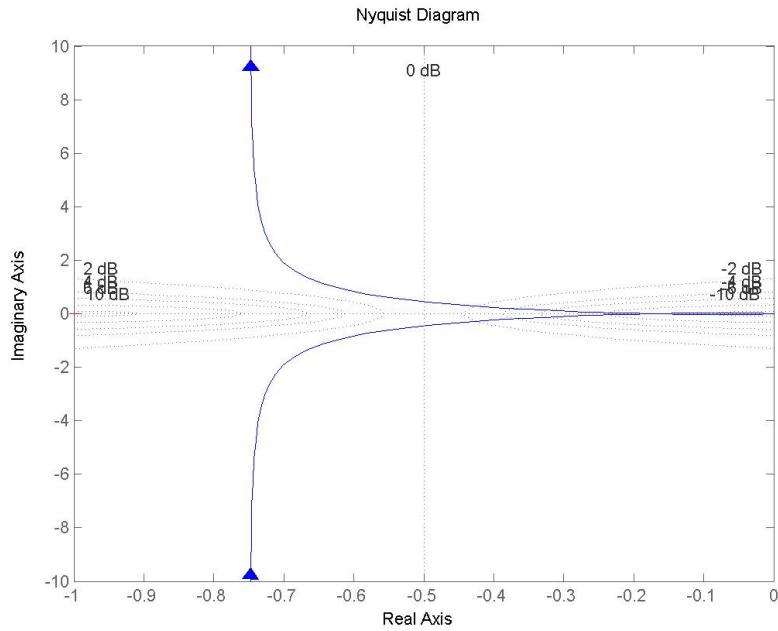


Figura 136: Diagrama de Nyquist do sistema sem compensação

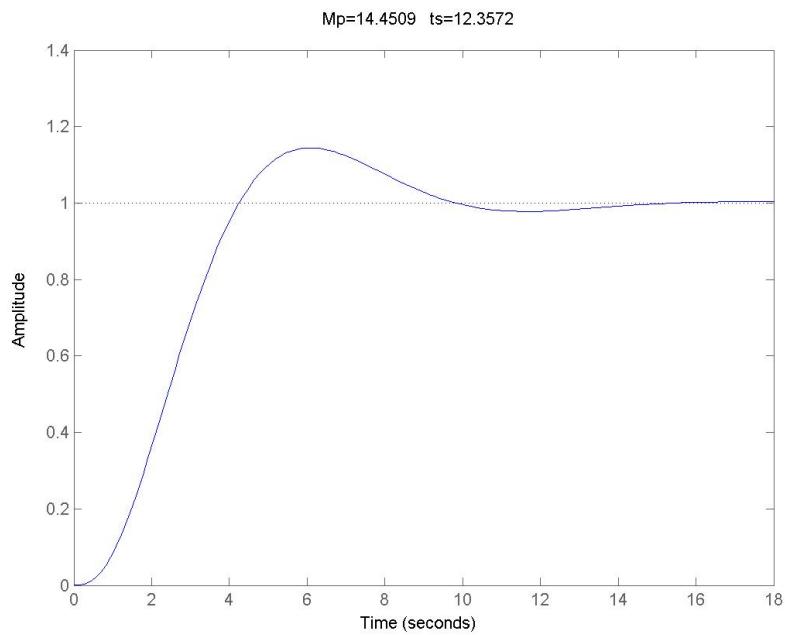


Figura 137: Resposta do sistema ao degrau unitário sem compensação

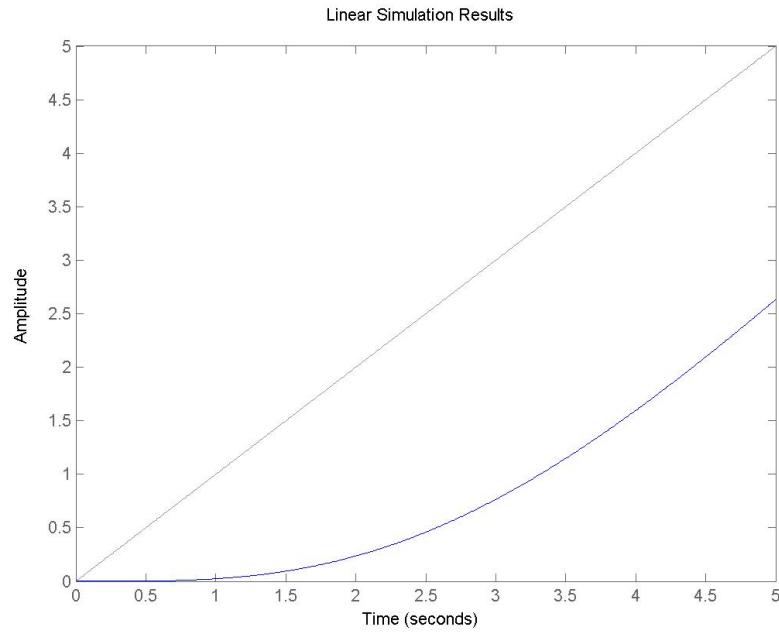


Figura 138: Resposta do sistema a rampa unitária sem compensação

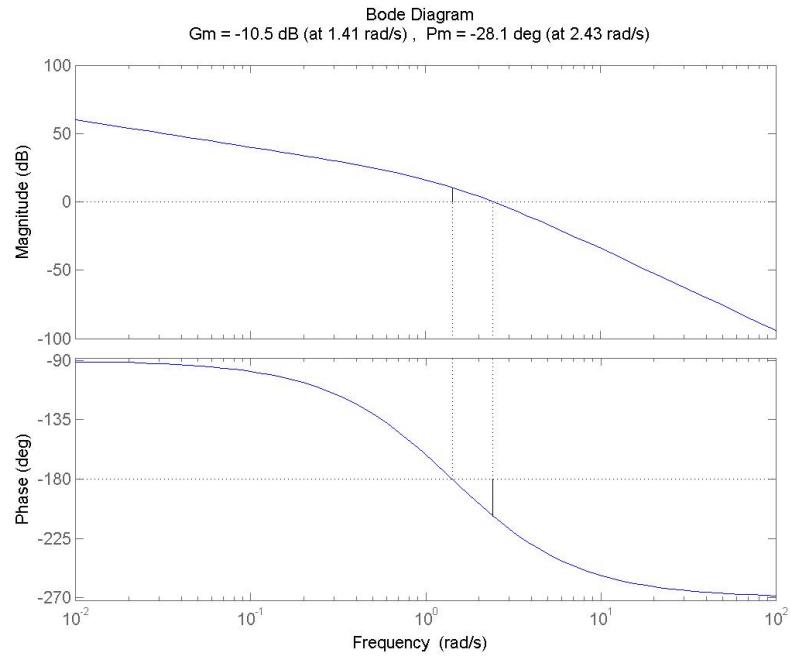


Figura 139: Diagrama de Bode do sistema com ajuste de ganho

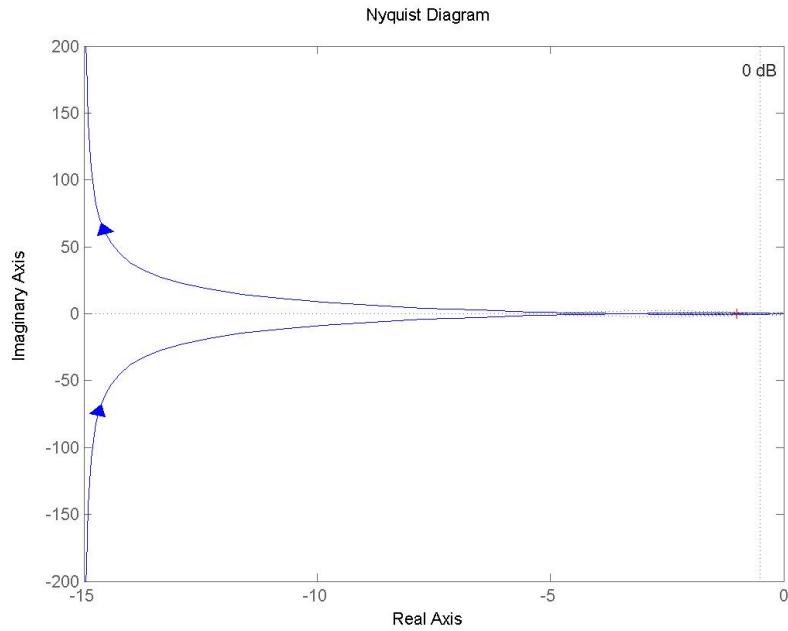


Figura 140: Diagrama de Nyquist do sistema com ajuste de ganho

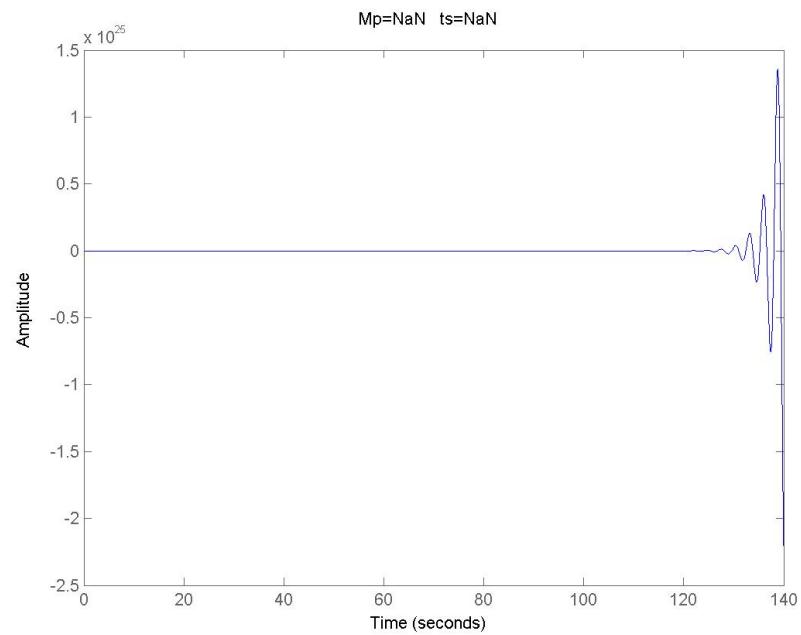


Figura 141: Resposta do sistema ao degrau unitário com ajuste de ganho

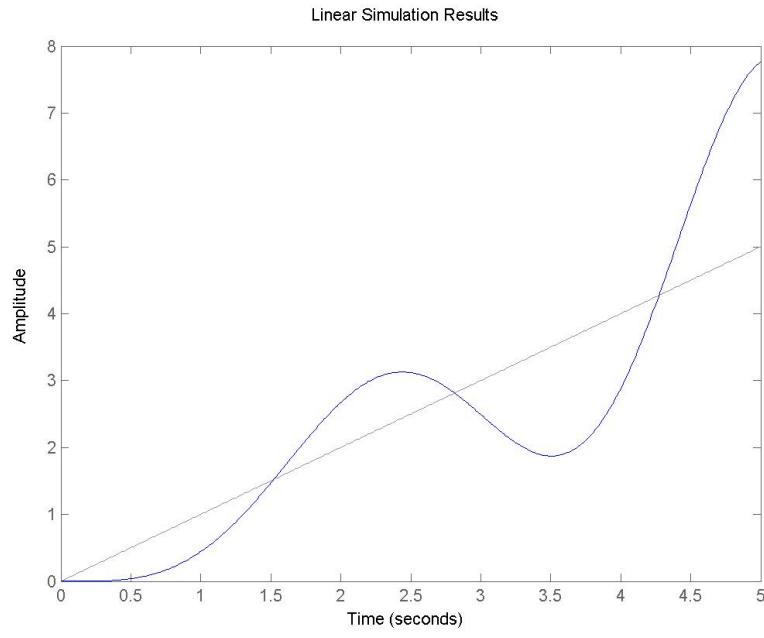


Figura 142: Resposta do sistema a rampa unitária com ajuste de ganho

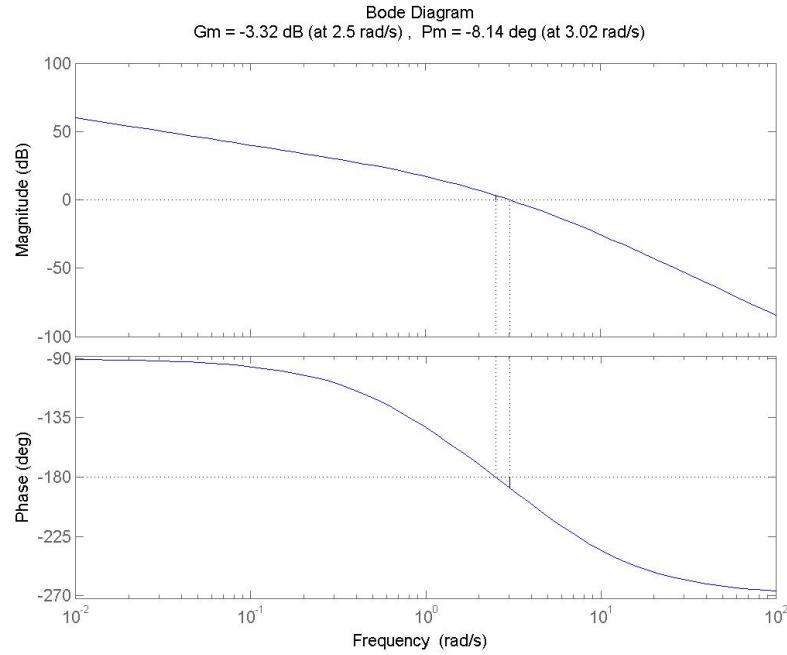


Figura 143: Diagrama de Bode do sistema com avanço de fase

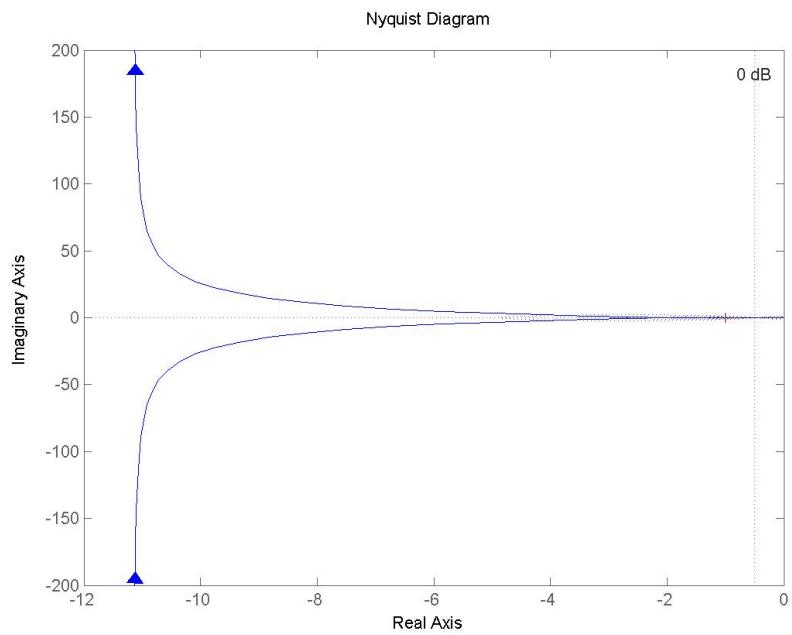


Figura 144: Diagrama de Nyquist do sistema com avanço de fase

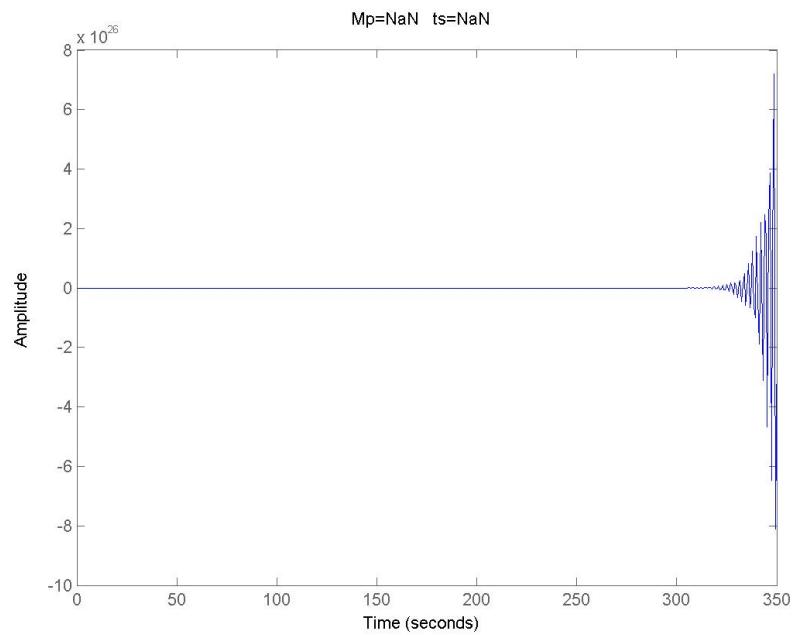


Figura 145: Resposta do sistema ao degrau unitário compensado por avanço

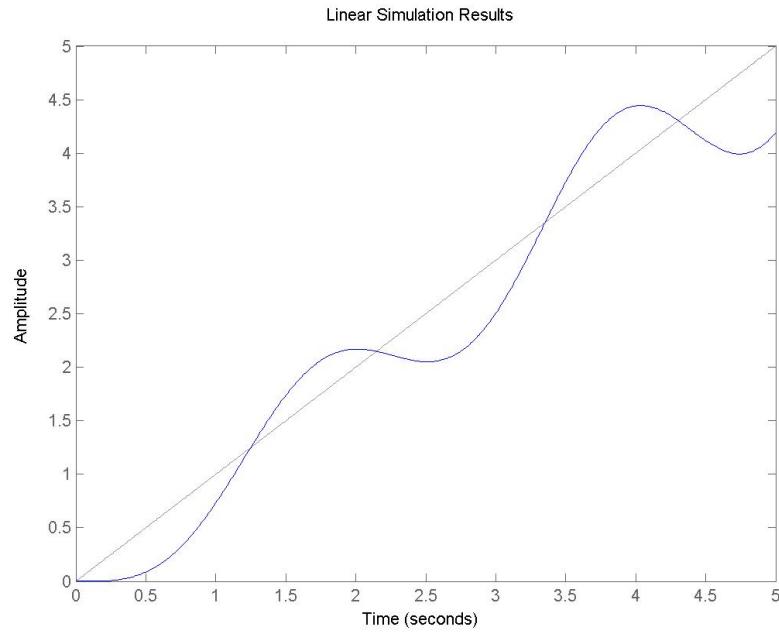


Figura 146: Resposta do sistema a rampa unitária compensado por avanço

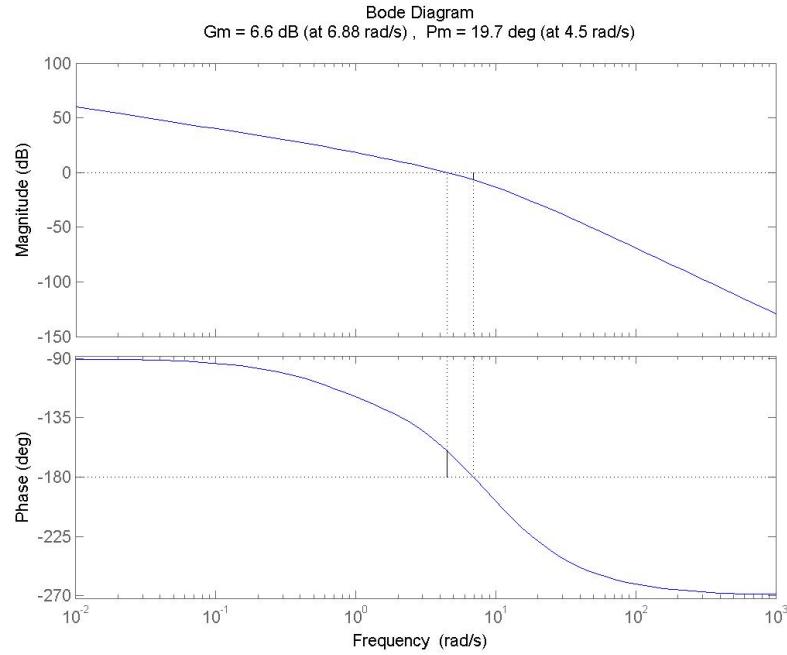


Figura 147: Diagrama de Bode do sistema com avanço-avanço de fase

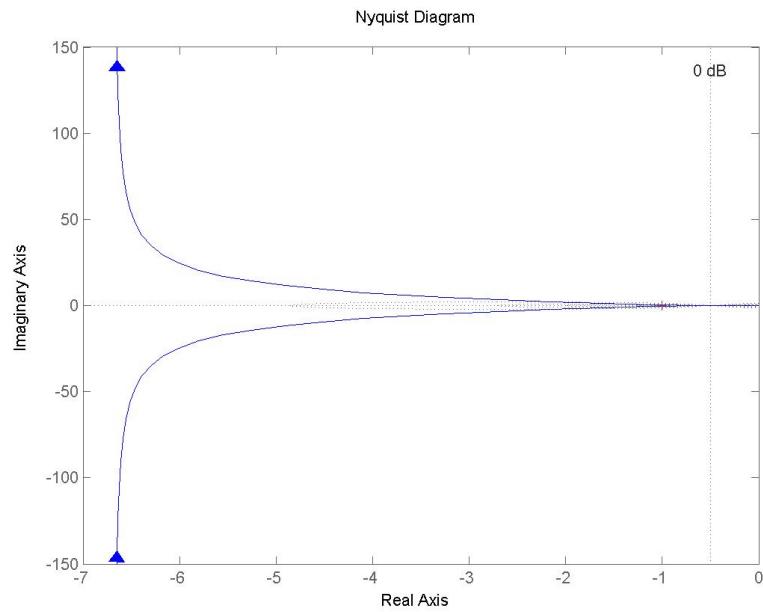


Figura 148: Diagrama de Nyquist do sistema com avanço-avanço de fase

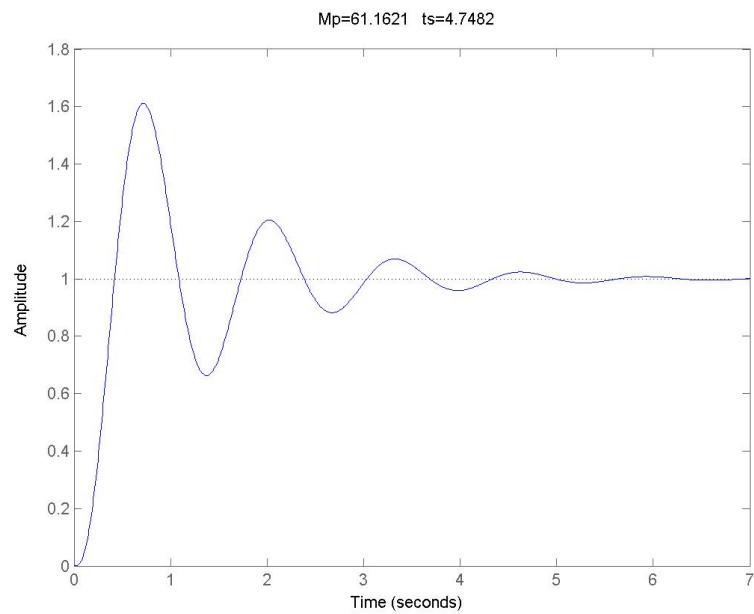


Figura 149: Resposta do sistema ao degrau unitário compensado por avanço-avanço

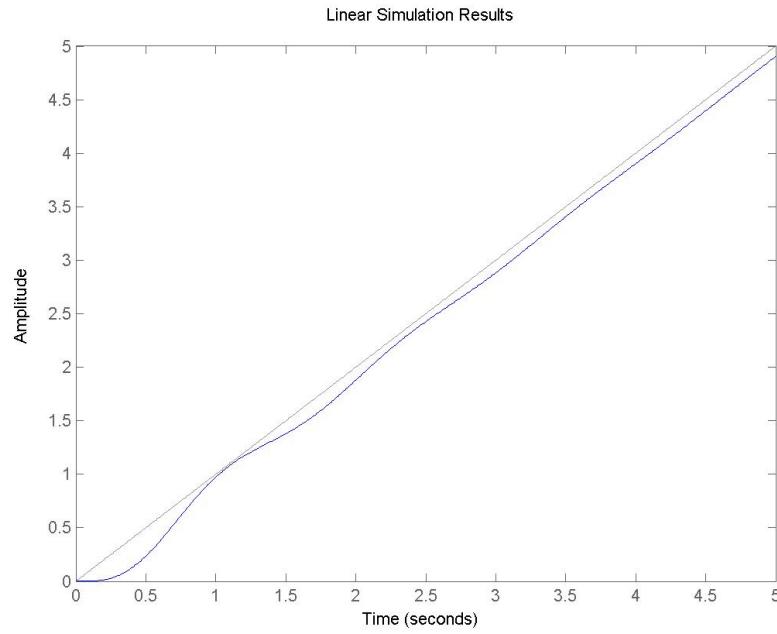


Figura 150: Resposta do sistema a rampa unitária compensado por avanço-avanço

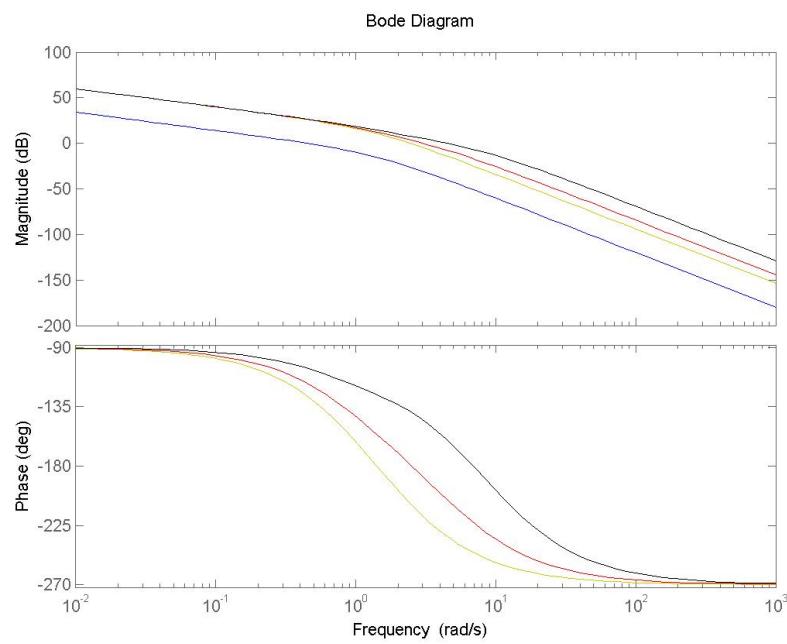


Figura 151: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

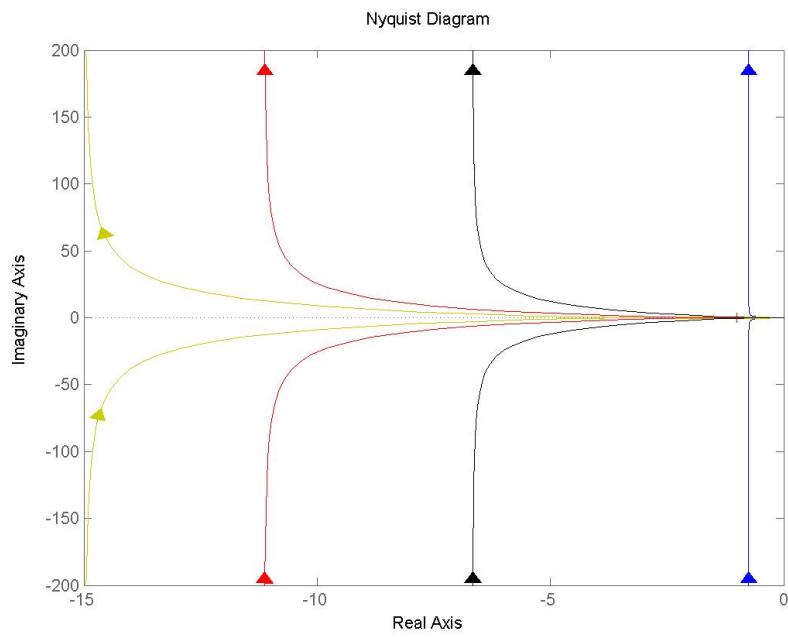


Figura 152: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

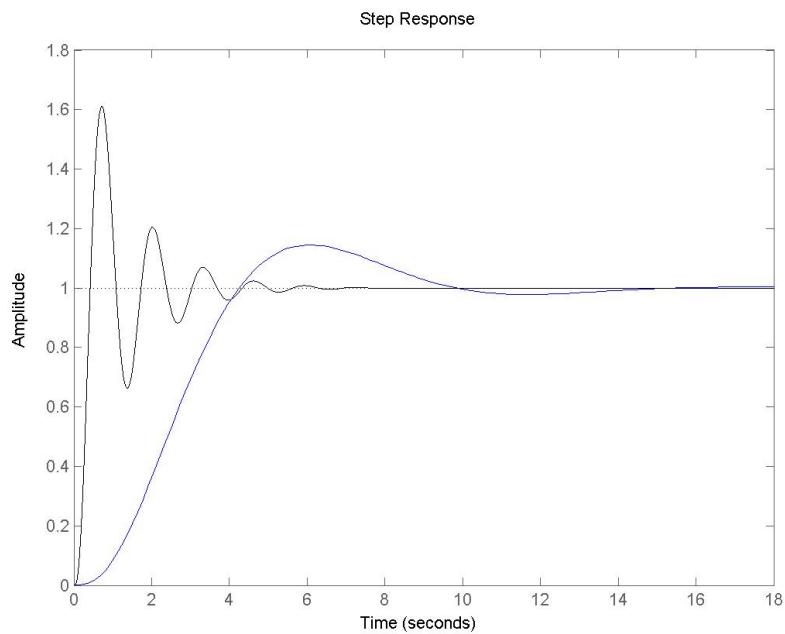


Figura 153: $G(s)$ (azul) - $K_c \cdot G(s)$ (vermelho) - $K_c \cdot G_{av}(s) \cdot G(s)$ (preto)

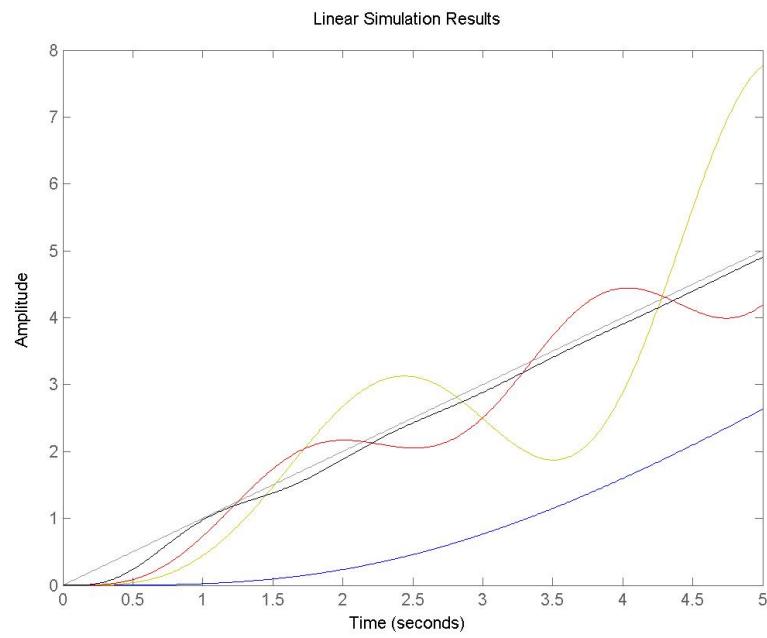


Figura 154: $G(s)$ (azul) - $K_c.G(s)$ (vermelho) - $K_c.G_{av}(s).G(s)$ (preto)

A Rotinas em Matlab

A.1 Exercicio

```
clc
close all
clear all

% Requisitos do sistema
Mp = 0.1;
ess = 0.005;
ts = 1;

% Sistema sem compensação
num = 0.0374;
den = conv([0.01 1 0],[0.657 1]);
sys = tf(num,den)
sysMF = feedback(sys,1)
t = 0:0.01:5;

% Diagrama de Bode do sistema sem compensação
figure(1)
margin(sys)
print('EX1-DBMA',' -djpeg')

figure(2)
nyquist(sys)
grid on
print('EX1-DNMA',' -djpeg')

figure(3)
step(sysMF)
S1 = stepinfo(feedback(sys,1), 'RiseTimeLimits', [0.02,0.98]);
Mp1 = S1.Overshoot;
ts1 = S1.SettlingTime;
title(['Mp=', num2str(Mp1), ' ts=', num2str(ts1)]);
print('EX1-Step',' -djpeg')

figure(4)
lsim(sysMF,t,t)
print('EX1-Ramp',' -djpeg')

% Sistema com ganho ajustado
K = 200/0.0374;
numKc = K*num;
denKc = den;
sysKc = tf(numKc,denKc)
sysKcMF = feedback(sysKc,1)
```

```

% Diagrama de Bode do sistema com ganho ajustado
figure(5)
margin(sysKc)
print('EX1-DBMA_Kc', '-djpeg')

% Resposta ao degrau do sistema com ganho ajustado
[Gm,Pm,Wg,Wp] = margin(sysKc);

figure(6)
nyquist(sysKc)
grid on
print('EX1-DNMA_Kc', '-djpeg')

figure(7)
step(sysKcMF)
S2 = stepinfo(feedback(sysKc,1), 'RiseTimeLimits', [0.02,0.98]);
Mp2 = S2.Overshoot;
ts2 = S2.SettlingTime;
title(['Mp=',num2str(Mp2), ' ts=', num2str(ts2)]);
print('EX1-Step_Kc', '-djpeg')

figure(8)
lsim(sysKcMF,t,t)
print('EX1-Ramp_Kc', '-djpeg')

% Projeto do controlador por atraso
qui = -log(Mp)/(sqrt(pi^2 + (log(Mp))^2));

Mfase = atan( 2*qui/(sqrt(-2*qui^2 + sqrt(1 + 4*qui^4))) )*(180/pi);
tolerancia = 12;

phi_n = -180 + 30 + tolerancia;

wn = 1.65;
ganhol = 38.3;

beta = 10^(ganhol/20);

% Calculo do T1
Tat = 10/wn;

numat = [Tat 1];
denat = [beta*Tat 1];
sysat = tf(numat,denat)

sysparcial = tf(series(sysKc,sysat))
sysparcialMF = feedback(sysparcial,1)

figure(9)
margin(sysparcial);
print('EX1-DBMA_Gat', '-djpeg')

```

```

figure(10)
nyquist(sysparcial)
grid on
print('EX1-DNMA_Gat', '-djpeg')

figure(11)
step(sysparcialMF)
S3 = stepinfo(feedback(sysparcial,1), 'RiseTimeLimits', [0.02,0.98]);
Mp3 = S3.Overshoot;
ts3 = S3.SettlingTime;
title(['Mp=', num2str(Mp3), ' ts=', num2str(ts3)]);
print('EX1-Step_Gat', '-djpeg')

figure(12)
lsim(sysparcialMF,t,t)
print('EX1-Ramp_Gat', '-djpeg')

% Projeto do controlador por avanço
Pm = 36;

phi_m = Mfase - Pm + tolerancia;
alpha = (1 - sin(phi_m*pi/180))/(1 + sin(phi_m*pi/180));
ganho2 = -20*log10(1/sqrt(alpha));
wm = 2.45;

% Calculo do T
Tav = 1/(wm*sqrt(alpha));

numav = [Tav 1];
denav = [alpha*Tav 1];
sysav = tf(numav,denav)

sysfinal = tf(series(sysparcial,sysav))
sysfinalMF = feedback(sysfinal,1)

figure(13)
margin(sysfinal);
print('EX1-DBMA_Gat_av', '-djpeg')

figure(14)
nyquist(sysfinal)
grid on
print('EX1-DNMA_Gat_av', '-djpeg')

figure(15)
step(sysfinalMF)
S4 = stepinfo(feedback(sysfinal,1), 'RiseTimeLimits', [0.02,0.98]);

```

```

Mp4 = S4.Overshoot;
ts4 = S4.SettlingTime;
title(['Mp=',num2str(Mp4), ' ts=', num2str(ts4)]);
print('EX1-Step_Gat_av','-djpeg')

figure(16)
lsim(sysfinalMF,t,t)
print('EX1-Ramp_Gat_av','-djpeg')

figure(17)
bode(sys,'b')
hold on
bode(sysKc,'y')
bode(syspartial,'r')
bode(sysfinal,'k')
print('EX1-DBMA_compare','-djpeg')

figure(18)
nyquist(sys,'b')
hold on
nyquist(sysKc,'y')
nyquist(syspartial,'r')
nyquist(sysfinal,'k')
print('EX1-DNMA_compare','-djpeg')

figure(19)
step(sysMF,'b')
hold on
step(sysKcMF,'y')
step(syspartialMF,'r')
step(sysfinalMF,'k')
print('EX1-Step_compare','-djpeg')

figure(20)
lsim(sysMF,'b',t,t)
hold on
lsim(sysKc,'y',t,t)
lsim(syspartial,'r',t,t)
lsim(syspartialMF,'k',t,t)
print('EX1-Ramp_compare','-djpeg')

```

A.2 Exercicio

```
clc
close all
clear all

% Requisitos do sistema
ess = 0.005;
Mfase = 45;

% Sistema sem compensação
num = 0.0374;
den = conv([0.01 1 0],[0.657 1]);
sys = tf(num,den)
sysMF = feedback(sys,1)
t = 0:0.01:5;

% Diagrama de Bode do sistema sem compensação
figure(1)
margin(sys)
print('EX2-DBMA', '-djpeg')

figure(2)
nyquist(sys)
grid on
print('EX2-DNMA', '-djpeg')

figure(3)
step(sysMF)
S1 = stepinfo(feedback(sys,1), 'RiseTimeLimits', [0.02,0.98]);
Mp1 = S1.Overshoot;
ts1 = S1.SettlingTime;
title(['Mp=', num2str(Mp1), ' ts=', num2str(ts1)]);
print('EX2-Step', '-djpeg')

figure(4)
lsim(sysMF,t,t);
print('EX2-Ramp', '-djpeg')

% Sistema com ganho ajustado mas não compensado
K = 200/0.0374;
numKc = K*num;
denKc = den;
sysKc = tf(numKc,denKc)
sysKcMF = feedback(sysKc,1)

% Diagrama de Bode do sistema com ganho ajustado
figure(5)
margin(sysKc)
print('EX2-DBMA_Kc', '-djpeg')
```

```

% Resposta ao degrau do sistema com ganho ajustado
[Gm,Pm,Wg,Wp] = margin(sysKc);

figure(6)
nyquist(sysKc)
grid on
print('EX2-DNMA_Kc',' -djpeg')

figure(7)
step(sysKcMF)
S2 = stepinfo(feedback(sysKc,1), 'RiseTimeLimits', [0.02,0.98]);
Mp2 = S2.Overshoot;
ts2 = S2.SettlingTime;
title(['Mp=' , num2str(Mp2), ' ts=' , num2str(ts2)]);
print('EX2-Step_Kc',' -djpeg')

figure(8)
lsim(sysKcMF,t,t);
print('EX2-Ramp_Kc',' -djpeg')

% Projeto do controlador
tole = 10;
Pm = -4.77; % Diagrama de bode com ganho ajustado
phi_m = Mfase - Pm + tole;

alpha = (1 - sin(phi_m*pi/180))/(1 + sin(phi_m*pi/180));
atenuacao = -20*log10(1/sqrt(alpha));
wm = 32.7;

% Calculo do T
T = 1/(wm*sqrt(alpha));

numav = [T 1];
denav = [alpha*T 1];
sysav = tf(numav,denav)

sysfinal = tf(series(sysKc,sysav))
sysfinalMF = feedback(sysfinal,1)

figure(9)
margin(sysfinal);
print('EX2-DBMA_Gav',' -djpeg')

figure(10)
nyquist(sysfinal)
grid on
print('EX2-DNMA_Gav',' -djpeg')

```

```

figure(11)
step(sysfinalMF)
S3 = stepinfo(feedback(sysfinal,1), 'RiseTimeLimits', [0.02,0.98]);
Mp3 = S3.Overshoot;
ts3 = S3.SettlingTime;
title(['Mp=', num2str(Mp3), ' ts=', num2str(ts3)]);
print('EX2-Step_Gav', '-djpeg')

figure(12)
lsim(sysfinalMF,t,t);
print('EX2-Ramp_Gav', '-djpeg')

figure(13)
bode(sys, 'b')
hold on
bode(sysKc, 'r')
bode(sysfinal, 'k')
print('EX2-DBMA_compare', '-djpeg')

figure(14)
nyquist(sys, 'b')
hold on
nyquist(sysKc, 'r')
nyquist(sysfinal, 'k')
print('EX2-DNMA_compare', '-djpeg')

figure(15)
step(sysMF, 'b')
hold on
step(sysKcMF, 'r')
step(sysfinalMF, 'k')
print('EX2-Step_compare', '-djpeg')

figure(16)
lsim(sysMF, 'b',t,t);
hold on
lsim(sysKcMF, 'r',t,t);
lsim(sysfinalMF, 'k',t,t);
print('EX2-Ramp_compare', '-djpeg')

```

A.3 Exercicio

A.4 Exercicio

```
clc
close all
clear all

% Requisitos do sistema
ess = 0.01;
Mp = 0.05;
tr = 0.02;
ts = 0.02;

% Sistema sem compensação
num = 2500;
den = [1 25 0];
sys = tf(num,den)
sysMF = feedback(sys,1)
t = 0:0.01:5;

% Diagrama de Bode do sistema sem compensação
figure(1)
margin(sys)
print('EX4-DBMA', '-djpeg')

figure(2)
nyquist(sys)
grid on
print('EX4-DNMA', '-djpeg')

figure(3)
step(sysMF)
S1 = stepinfo(feedback(sys,1), 'RiseTimeLimits',[0.02,0.98]);
Mp1 = S1.Overshoot;
ts1 = S1.SettlingTime;
title(['Mp=', num2str(Mp1), ' ts=', num2str(ts1)]);
print('EX4-Step', '-djpeg')

figure(4)
lsim(sysMF,t,t);
print('EX4-Ramp', '-djpeg')

% Sistema com ganho ajustado mas não compensado
K = 1;
numKc = K*num;
denKc = den;
sysKc = tf(numKc,denKc)
sysKcMF = feedback(sysKc,1)

% Diagrama de Bode do sistema com ganho ajustado
figure(5)
```

```

margin(sysKc)
print('EX4-DBMA_Kc', '-djpeg')

% Resposta ao degrau do sistema com ganho ajustado
[Gm, Pm, Wg, Wp] = margin(sysKc);

figure(6)
nyquist(sysKc)
grid on
print('EX4-DNMA_Kc', '-djpeg')

figure(7)
step(sysKcMF)
S2 = stepinfo(feedback(sysKc,1), 'RiseTimeLimits', [0.02,0.98]);
Mp2 = S2.Overshoot;
ts2 = S2.SettlingTime;
title(['Mp=', num2str(Mp2), ' ts=', num2str(ts2)]);
print('EX4-Step_Kc', '-djpeg')

figure(8)
lsim(sysKcMF,t,t);
print('EX4-Ramp_Kc', '-djpeg')

% Projeto do controlador
qui = -log(Mp)/(sqrt(pi^2 + (log(Mp))^2));
% Mfase = atan( 2*qui/(sqrt(-2*qui^2 + sqrt(1 + 4*qui^4))) )*(180/pi);
Mfase = 100*qui;

tole = 5;
Pm = 28; % Diagrama de bode com ganho ajustado
phi_m = Mfase - Pm + tole;

alpha = (1 - sin(phi_m*pi/180))/(1 + sin(phi_m*pi/180));
atenuacao = -20*log10(1/sqrt(alpha));

wm = 76.7;

% Calculo do T
T = 1/(wm*sqrt(alpha));

numav = [T 1];
denav = [alpha*T 1];
sysav = tf(numav,denav)

sysfinal = tf(series(sysKc,sysav))
sysfinalMF = feedback(sysfinal,1)

figure(9)
margin(sysfinal);
print('EX4-DBMA_Gav', '-djpeg')

```

```

figure(10)
nyquist(sysfinal)
grid on
print('EX4-DNMA_Gav', '-djpeg')

figure(11)
step(sysfinalMF)
S3 = stepinfo(feedback(sysfinal,1), 'RiseTimeLimits', [0.02,0.98]);
Mp3 = S3.Overshoot;
ts3 = S3.SettlingTime;
title(['Mp=', num2str(Mp3), ' ts=', num2str(ts3)]);
print('EX4-Step_Gav', '-djpeg')

figure(12)
lsim(sysfinalMF,t,t);
print('EX4-Ramp_Gav', '-djpeg')

figure(13)
bode(sys, 'b')
hold on
bode(sysKc, 'r')
bode(sysfinal, 'k')
print('EX4-DBMA_compare', '-djpeg')

figure(14)
nyquist(sys, 'b')
hold on
nyquist(sysKc, 'r')
nyquist(sysfinal, 'k')
print('EX4-DNMA_compare', '-djpeg')

figure(15)
step(sysMF, 'b')
hold on
step(sysKcMF, 'r')
step(sysfinalMF, 'k')
print('EX4-Step_compare', '-djpeg')

figure(16)
lsim(sysMF, 'b', t,t);
hold on
lsim(sysKcMF, 'r', t,t);
lsim(sysfinalMF, 'k', t,t);
print('EX4-Ramp_compare', '-djpeg')

```

A.5 Exercicio

```
clc
close all
clear all

% Requisitos do sistema
Mp = 0.05;
ts = 5;

% Sistema sem compensação
num = 16*[1 1];
den = conv([1 0],[1 2 16]);
sys = tf(num,den)
sysMF = feedback(sys,1)
t = 0:0.01:5;

% Diagrama de Bode do sistema sem compensação
figure(1)
margin(sys)
print('EX5-DBMA',' -djpeg')

figure(2)
nyquist(sys)
grid on
print('EX5-DNMA',' -djpeg')

figure(3)
step(sysMF)
S1 = stepinfo(feedback(sys,1), 'RiseTimeLimits', [0.02,0.98]);
Mpl = S1.Overshoot;
ts1 = S1.SettlingTime;
title(['Mp=', num2str(Mpl), ' ts=', num2str(ts1)]);
print('EX5-Step',' -djpeg')

figure(4)
lsim(sysMF,t,t)
print('EX5-Ramp',' -djpeg')

% Projeto do controlador
qui = -log(Mp)/(sqrt(pi^2 + (log(Mp))^2));
Mfase = atan( 2*qui/(sqrt( 1 + 4*qui^4 ) - 2*qui^2 ))*(180/pi);
tole = 9;
Pm = 30.2; % Diagrama de bode com ganho ajustado

phi_m = Mfase - Pm + tole;

alpha = (1 - sin(phi_m*pi/180))/(1 + sin(phi_m*pi/180));
```

```

atenuacao = -20*log10(1/sqrt(alpha));

wm = 7.13;

% Calculo do T
T = 1/(wm*sqrt(alpha));

numc = [T 1];
denc = [alpha*T 1];
sysc = tf(numc,denc)

sysfinal = tf(series(sys,sysc))
sysfinalMF = feedback(sysfinal,1)

figure(5)
margin(sysfinal);
print('EX5-DBMA_Gav', '-djpeg')

figure(6)
nyquist(sysfinal)
grid on
print('EX5-DNMA_Gav', '-djpeg')

figure(7)
step(sysfinalMF)
S2 = stepinfo(feedback(sysfinal,1), 'RiseTimeLimits', [0.02,0.98]);
Mp2 = S2.Overshoot;
ts2 = S2.SettlingTime;
title(['Mp=', num2str(Mp2), ' ts=', num2str(ts2)]);
print('EX5-Step_Gav', '-djpeg')

figure(8)
lsim(sysfinalMF,t,t)
print('EX5-Ramp_Gav', '-djpeg')

figure(9)
bode(sys, 'b')
hold on
bode(sysfinal, 'k')
print('EX5-DBMA_compare', '-djpeg')

figure(10)
nyquist(sys, 'b')
hold on
nyquist(sysfinal, 'k')
print('EX5-DNMA_compare', '-djpeg')

figure(11)
step(sysMF, 'b')
hold on
step(sysfinalMF, 'k')

```

```
print('EX5-Step_compare', '-djpeg')

figure(12)
lsim(sysMF, 'b', t, t)
hold on
lsim(sysfinalMF, 'k', t, t)
print('EX5-Ramp_compare', '-djpeg')
```

A.6 Exercicio

```
clc
close all
clear all

% Requisitos de Projeto
ess = 0.1;
qui = 0.707;

% Sistema sem compensação
num    = 1;
den    = conv([1 10 0],[1 14]);
sys    = tf(num,den)
sysMF = feedback(sys,1)
t      = 0:0.01:5;

% Diagrama de Bode do sistema sem compensação
figure(1)
margin(sys)
print('EX6-DBMA',' -djpeg')

figure(2)
nyquist(sys)
grid on
print('EX6-DNMA',' -djpeg')

figure(3)
step(sysMF)
S1 = stepinfo(feedback(sys,1), 'RiseTimeLimits', [0.02,0.98]);
Mp1 = S1.Overshoot;
ts1 = S1.SettlingTime;
title(['Mp=', num2str(Mp1), ' ts=', num2str(ts1)]);
print('EX6-Step',' -djpeg')

figure(4)
lsim(sysMF,t,t)
print('EX6-Ramp',' -djpeg')

% Sistema com ganho ajustado mas não compensado
K = 1400;
numKc   = K*num;
denKc   = den;
sysKc   = tf(numKc,denKc)
sysKcMF = feedback(sysKc,1);

% Diagrama de Bode do sistema com ganho ajustado
figure(5)
margin(sysKc)
print('EX6-DBMA_Kc',' -djpeg')
```

```

% Resposta ao degrau do sistema com ganho ajustado
[Gm,Pm,Wg,Wp] = margin(sysKc);

figure(6)
nyquist(sysKc)
grid on
print('EX6-DNMA_Kc',' -djpeg')

figure(7)
step(sysKcMF)
S2 = stepinfo(feedback(sysKc,1), 'RiseTimeLimits', [0.02,0.98]);
Mp2 = S2.Overshoot;
ts2 = S2.SettlingTime;
title(['Mp=' , num2str(Mp2), ' ts=' , num2str(ts2)]);
print('EX6-Step_Kc',' -djpeg')

figure(8)
lsim(sysKcMF,t,t)
print('EX6-Ramp_Kc',' -djpeg')

% Projeto do controlador
tolerancia = 5;
Mfase = atan( 2*qui/(sqrt( sqrt(1 + 4*qui^4) - 2*qui^2 )) )*(180/pi);
phi_m = Mfase - 180 + tolerancia;

wn = 2.09; %rad/s
atenuacao = 13.3; %dB

beta = 10^(atenuacao/20);

% Calculo do T
T = 10/wn;

numAt = [T 1];
denAt = [beta*T 1];
sysAt = tf(numAt,denAt)

sysfinal = tf(series(sysKc,sysAt))
sysfinalMF = feedback(sysfinal,1)

figure(9)
margin(sysfinal);
print('EX6-DBMA_Gat',' -djpeg')

figure(10)
nyquist(sysfinal)
grid on
print('EX6-DNMA_Gat',' -djpeg')

figure(11)

```

```

step(sysfinalMF)
S3 = stepinfo(feedback(sysfinal,1), 'RiseTimeLimits', [0.02,0.98]);
Mp3 = S3.Overshoot;
ts3 = S3.SettlingTime;
title(['Mp=', num2str(Mp3), ' ts=', num2str(ts3)]);
print('EX6-Step_Gat', '-djpeg')

figure(12)
lsim(sysfinalMF,t,t)
print('EX6-Ramp_Gat', '-djpeg')

figure(13)
bode(sys, 'b')
hold on
bode(sysKc, 'r')
bode(sysfinal, 'k')
print('EX6-DBMA_compare', '-djpeg')

figure(14)
nyquist(sys, 'b')
hold on
nyquist(sysKc, 'r')
nyquist(sysfinal, 'k')
print('EX6-DNMA_compare', '-djpeg')

figure(15)
step(sysMF, 'b')
hold on
step(sysKcMF, 'r')
step(sysfinalMF, 'k')
print('EX6-Step_compare', '-djpeg')

figure(16)
lsim(sysMF, 'b', t,t)
hold on
lsim(sysKcMF, 'r', t,t)
lsim(sysfinalMF, 'k', t,t)
print('EX6-Ramp_compare', '-djpeg')

```

A.7 Exercício

```
clc
close all
clear all

% Requisitos do sistema
ess = 0.01;
Mr = 3.5;
wr = 1.4;

% Sistema sem compensação
num    = 10*[-1 40];
den    = conv([1 10 0 0],[1 40]);
sys    = tf(num,den)
sysMF = feedback(sys,1)
t      = 0:0.01:5;

% Diagrama de Bode do sistema sem compensação
figure(1)
margin(sys)
print('EX7-DBMA','-djpeg')

figure(2)
nyquist(sys)
grid on
print('EX7-DNMA','-djpeg')

figure(3)
step(sysMF)
S1 = stepinfo(feedback(sys,1), 'RiseTimeLimits', [0.02,0.98]);
Mp1 = S1.Overshoot;
ts1 = S1.SettlingTime;
title(['Mp=', num2str(Mp1), ' ts=', num2str(ts1)]);
print('EX7-Step','-djpeg')

figure(4)
lsim(sysMF,t,t)
print('EX7-Ramp','-djpeg')

% Projeto do controlador
qui = sqrt( (1 - sqrt(1 - 1/(Mr^2)) ) /2 );
Mfase = atan( 2*qui/(sqrt(-2*qui^2 + sqrt(1 + 4*qui^4))) )*(180/pi);

tole = 5;
Pm = -8.55; % Diagrama de bode com ganho ajustado
phi_m = Mfase - Pm + tole;

alpha = (1 - sin(phi_m*pi/180))/(1 + sin(phi_m*pi/180));
```

```

atenuacao = -20*log10(1/sqrt(alpha));

wm = 1.31;

% Calculo do T
T = 1/(wm*sqrt(alpha));

numav = [T 1];
denav = [alpha*T 1];
sysav = tf(numav,denav)

sysfinal = tf(series(sys,sysav))
sysfinalMF = feedback(sysfinal,1)

figure(5)
margin(sysfinal);
print('EX7-DBMA_Gav', '-djpeg')

figure(6)
nyquist(sysfinal)
grid on
print('EX7-DNMA_Gav', '-djpeg')

figure(7)
step(feedback(sysfinal,1))
S2 = stepinfo(feedback(sysfinal,1), 'RiseTimeLimits', [0.02,0.98]);
Mp2 = S2.Overshoot;
ts2 = S2.SettlingTime;
title(['Mp=', num2str(Mp2), ' ts=', num2str(ts2)]);
print('EX7-Step_Gav', '-djpeg')

figure(8)
lsim(sysMF,t,t)
print('EX7-Ramp_Gav', '-djpeg')

figure(9)
bode(sys, 'b')
hold on
bode(sysfinal, 'k')
print('EX7-DBMA_compare', '-djpeg')

figure(10)
nyquist(sys, 'b')
hold on
nyquist(sysfinal, 'k')
print('EX7-DNMA_compare', '-djpeg')

figure(11)
step(sysMF, 'b')
hold on
step(sysfinalMF, 'k')

```

```
print('EX7-Step_compare', '-djpeg')

figure(12)
lsim(sysMF, 'b', t, t)
hold on
lsim(sysfinalMF, 'k', t, t)
print('EX7-Ramp_compare', '-djpeg')
```

A.8 Exercicio

```
clc
close all
clear all

% Requisitos de Projeto
ess = 0.025;
qui = 0.7;
Mp = 0.05;

% Sistema sem compensação
num1 = 5;
den1 = [0.1 1];
sys1 = tf(num1,den1)
num2 = 1;
den2 = [0.001 0.01 0];
sys2 = tf(num2,den2)
sys = series(sys1,0.1*sys2)
sysMF = feedback(sys,1)
t = 0:0.01:5;

% Diagrama de Bode do sistema sem compensação
figure(1)
margin(sys)
print('EX8-DBMA', '-djpeg')

figure(2)
nyquist(sys)
grid on
print('EX8-DNMA', '-djpeg')

figure(3)
step(sysMF)
S1 = stepinfo(feedback(sys,1), 'RiseTimeLimits', [0.02,0.98]);
Mp1 = S1.Overshoot;
ts1 = S1.SettlingTime;
title(['Mp=', num2str(Mp1), ' ts=', num2str(ts1)]);
print('EX8-Step', '-djpeg')

figure(4)
lsim(sysMF,t,t)
print('EX8-Ramp', '-djpeg')

% Sistema com ganho ajustado mas não compensado
K = 0.8;
sysKc = K*sys
sysKcMF = feedback(sysKc,1);

% Diagrama de Bode do sistema com ganho ajustado
```

```

figure(5)
margin(sysKc)
print('EX8-DBMA_Kc', '-djpeg')

% Resposta ao degrau do sistema com ganho ajustado
[Gm,Pm,Wg,Wp] = margin(sysKc);

figure(6)
nyquist(sysKc)
grid on
print('EX8-DNMA_Kc', '-djpeg')

figure(7)
step(sysKcMF)
S2 = stepinfo(feedback(sysKc,1), 'RiseTimeLimits', [0.02,0.98]);
Mp2 = S2.Overshoot;
ts2 = S2.SettlingTime;
title(['Mp=', num2str(Mp2), ' ts=', num2str(ts2)]);
print('EX8-Step_Kc', '-djpeg')

figure(8)
lsim(sysKcMF,t,t)
print('EX8-Ramp_Kc', '-djpeg')

% Projeto do controlador
tolerancia = 5;
Mfase = atan( 2*qui/(sqrt( sqrt(1 + 4*qui^4) - 2*qui^2 )) )*(180/pi);
phi_m = Mfase - 180 + tolerancia;

wn = 1.8; %rad/s
atenuacao = 26.7; %dB

beta = 10^(atenuacao/20);

% Calculo do T
T = 5/wn;

numAt = [T 1];
denAt = [beta*T 1];
sysAt = tf(numAt,denAt)

sysfinal = tf(series(sysKc,sysAt))
sysfinalMF = feedback(sysfinal,1)

figure(9)
margin(sysfinal);
print('EX8-DBMA_Gat', '-djpeg')

figure(10)
nyquist(sysfinal)
grid on

```

```

print('EX8-DNMA_Gat', '-djpeg')

figure(11)
step(sysfinalMF)
S3 = stepinfo(feedback(sysfinal,1), 'RiseTimeLimits', [0.02,0.98]);
Mp3 = S3.Overshoot;
ts3 = S3.SettlingTime;
title(['Mp=', num2str(Mp3), ' ts=', num2str(ts3)]);
print('EX8-Step_Gat', '-djpeg')

figure(12)
lsim(sysfinalMF,t,t)
print('EX8-Ramp_Gat', '-djpeg')

figure(13)
bode(sys, 'b')
hold on
bode(sysKc, 'r')
bode(sysfinal, 'k')
print('EX8-DBMA_compare', '-djpeg')

figure(14)
nyquist(sys, 'b')
hold on
nyquist(sysKc, 'r')
nyquist(sysfinal, 'k')
print('EX8-DNMA_compare', '-djpeg')

figure(15)
step(sysMF, 'b')
hold on
step(sysKcMF, 'r')
step(sysfinalMF, 'k')
print('EX8-Step_compare', '-djpeg')

figure(16)
lsim(sysMF, 'b', t, t)
hold on
lsim(sysKcMF, 'r', t, t)
lsim(sysfinalMF, 'k', t, t)
print('EX8-Ramp_compare', '-djpeg')

```

A.9 Exercicio

A.10 Exercicio

```
clc
close all
clear all

% Requisitos do sistema
Kp = 9;
Mfase = 25;

% Sistema sem compensação
num = 0.5;
den = conv([1 1 0], [0.5 1]);
sys = tf(num, den)
sysMF = feedback(sys, 1)
t = 0:0.01:5;

% Diagrama de Bode do sistema sem compensação
figure(1)
margin(sys)
print('EX10-DBMA', '-djpeg')

figure(2)
nyquist(sys)
grid on
print('EX10-DNMA', '-djpeg')

figure(3)
step(sysMF)
S1 = stepinfo(feedback(sys, 1), 'RiseTimeLimits', [0.02, 0.98]);
Mp1 = S1.Overshoot;
ts1 = S1.SettlingTime;
title(['Mp=' num2str(Mp1), ' ts=' num2str(ts1)]);
print('EX10-Step', '-djpeg')

figure(4)
lsim(sysMF, t, t);
print('EX10-Ramp', '-djpeg')

% Sistema com ganho ajustado mas não compensado
K = 10/0.5;
numKc = K*num;
denKc = den;
sysKc = tf(numKc, denKc)
sysKcMF = feedback(sysKc, 1)

% Diagrama de Bode do sistema com ganho ajustado
figure(5)
margin(sysKc)
print('EX10-DBMA_Kc', '-djpeg')
```

```

% Resposta ao degrau do sistema com ganho ajustado
[Gm,Pm,Wg,Wp] = margin(sysKc);

figure(6)
nyquist(sysKc)
grid on
print('EX10-DNMA_Kc',' -djpeg')

figure(7)
step(sysKcMF)
S2 = stepinfo(feedback(sysKc,1), 'RiseTimeLimits', [0.02,0.98]);
Mp2 = S2.Overshoot;
ts2 = S2.SettlingTime;
title(['Mp=' , num2str(Mp2), ' ts=' , num2str(ts2)]);
print('EX10-Step_Kc',' -djpeg')

figure(8)
lsim(sysKcMF,t,t);
print('EX10-Ramp_Kc',' -djpeg')

% Projeto do controlador
tolerancia = 12;
Pm = -28.1; % Diagrama de bode com ganho ajustado
phi_m = -10.1 - Pm + tolerancia;

alpha1 = (1 - sin(phi_m*pi/180))/(1 + sin(phi_m*pi/180));
ganho1 = -20*log10(1/sqrt(alpha1));

wm = 3;

% Calculo do T
T1 = 1/(wm*sqrt(alpha1));

numav1 = [T1 1];
denav1 = [alpha1*T1 1];
sysav1 = tf(numav1,denav1)

sysparcial = tf(series(sysKc,sysav1))
sysparcialMF = feedback(sysparcial,1)

figure(9)
margin(sysparcial)
print('EX10-DBMA_Gav',' -djpeg')

figure(10)
nyquist(sysparcial)
grid on
print('EX10-DNMA_Gav',' -djpeg')

```

```

figure(11)
step(sysparcialMF)
S3 = stepinfo(feedback(sysparcial,1), 'RiseTimeLimits', [0.02,0.98]);
Mp3 = S3.Overshoot;
ts3 = S3.SettlingTime;
title(['Mp=',num2str(Mp3), ' ts=', num2str(ts3)]);
print('EX10-Step_Gav',' -djpeg')

figure(12)
lsim(sysparcialMF,t,t);
print('EX10-Ramp_Gav',' -djpeg')

% Projeto do controlador por avanço
Pm = -8.14; % Diagrama de bode com ganho ajustado
phi_m = Mfase - Pm + tolerancia;

alpha2 = (1 - sin(phi_m*pi/180))/(1 + sin(phi_m*pi/180));
ganho2 = -20*log10(1/sqrt(alpha2));
wm = 4.49;

% Calculo do T
T2 = 1/(wm*sqrt(alpha2));

numav2 = [T2 1];
denav2 = [alpha2*T2 1];
sysav2 = tf(numav2,denav2)

sysfinal = tf(series(sysparcial,sysav2))
sysfinalMF = feedback(sysfinal,1)

figure(13)
margin(sysfinal);
print('EX10-DBMA_Gav_av',' -djpeg')

figure(14)
nyquist(sysfinal)
grid on
print('EX10-DNMA_Gav_av',' -djpeg')

figure(15)
step(sysfinalMF)
S4 = stepinfo(feedback(sysfinal,1), 'RiseTimeLimits', [0.02,0.98]);
Mp4 = S4.Overshoot;
ts4 = S4.SettlingTime;
title(['Mp=',num2str(Mp4), ' ts=', num2str(ts4)]);
print('EX10-Step_Gav_av',' -djpeg')

figure(16)
lsim(sysfinalMF,t,t);

```

```

print('EX10-Ramp_Gav_av', '-djpeg')

figure(17)
bode(sys, 'b')
hold on
bode(sysKc, 'y')
bode(sysparcial, 'r')
bode(sysfinal, 'k')
print('EX10-DBMA_compare', '-djpeg')

figure(18)
nyquist(sys, 'b')
hold on
nyquist(sysKc, 'y')
nyquist(sysparcial, 'r')
nyquist(sysfinal, 'k')
print('EX10-DNMA_compare', '-djpeg')

figure(19)
step(sysMF, 'b')
hold on
step(sysKcMF, 'y')
step(sysparcial, 'r')
step(sysfinalMF, 'k')
print('EX10-Step_compare', '-djpeg')

figure(20)
lsim(sysMF, 'b', t, t);
hold on
lsim(sysKcMF, 'y', t, t);
lsim(sysparcialMF, 'r', t, t);
lsim(sysfinalMF, 'k', t, t);
print('EX10-Ramp_compare', '-djpeg')

```