Escola Politécnica da Universidade de São Paulo
Departamento de Engenharia Mecatrônica e de Sistemas Mecânicos - PMR

Aula 10

Projeto de Controle – Exemplo Projeto em Frequência

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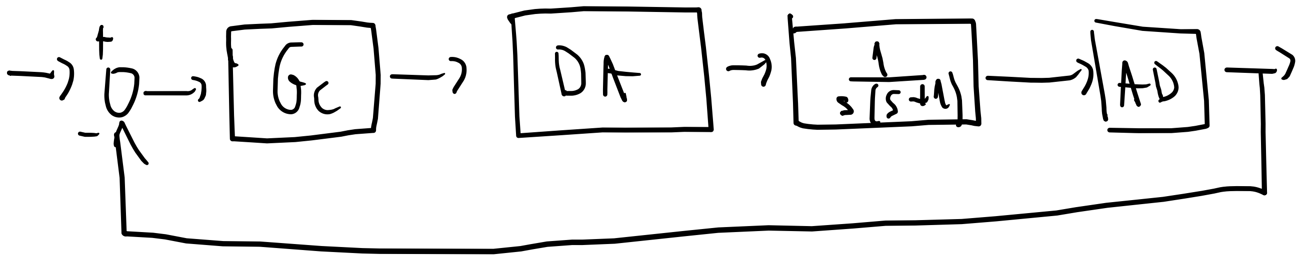
PMR 3409 – Controle II



- $G_c(z)$
- $e(\infty) = 0{,}3$ p/ ENTRADA RAMPA
- MF = 50°

1) FAZER PELO MÉTODO INDIRETO

$$G_{ZOH}(s) = \frac{1}{\frac{T_s}{2}s + 1} \rightarrow T_s = 0{,}2s$$

DA

1) VERIFICAR GANHO DO CONTROLADOR

$$e(\infty) = \lim s \cdot G_{MA}(s) = \cancel{s} \cdot \frac{1}{\cancel{s}(s+1)} \cdot \frac{1}{\frac{T}{2}s+1} \cdot K_{CONTROLE} = 0{,}3$$

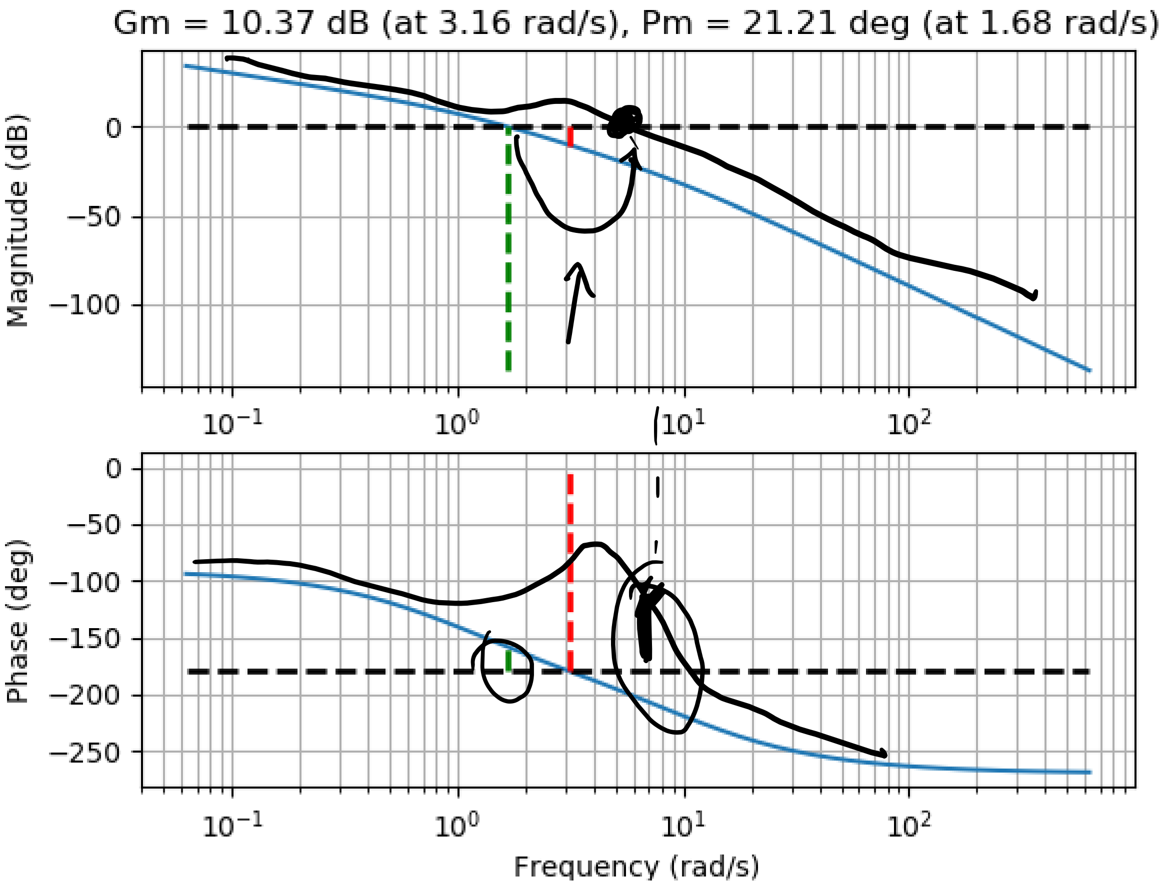
$$\Rightarrow \boxed{K_{CONTROLE} = 3{,}33}$$

$$G_C(s) = 3{,}33 \cdot \frac{s+p}{s+z}$$

AVANÇO OU ATRASO

2) MARGENS DO SISTEMA S/ COMPENSAÇÃO DINÂMICA

$$\text{MARGEM}\left(3{,}33 \cdot \frac{1}{s(s+1)} \cdot \frac{1}{\frac{T_s}{2}s+1}\right)$$



NÃO COMPENSADO

2) AVANÇO NECESSÁRIO

$$\phi_M = 50^\circ - 21^\circ + \underbrace{17^\circ}$$

DEVIDO AO AUMENTO DE ω_c

$$\mathrm{Sen}(\phi_M) = \frac{1-\alpha}{1+\alpha} \Rightarrow \underline{\alpha \cong 0{,}17}$$

$$G_c = K_c \cdot \frac{1+Ts}{1+\alpha Ts}$$

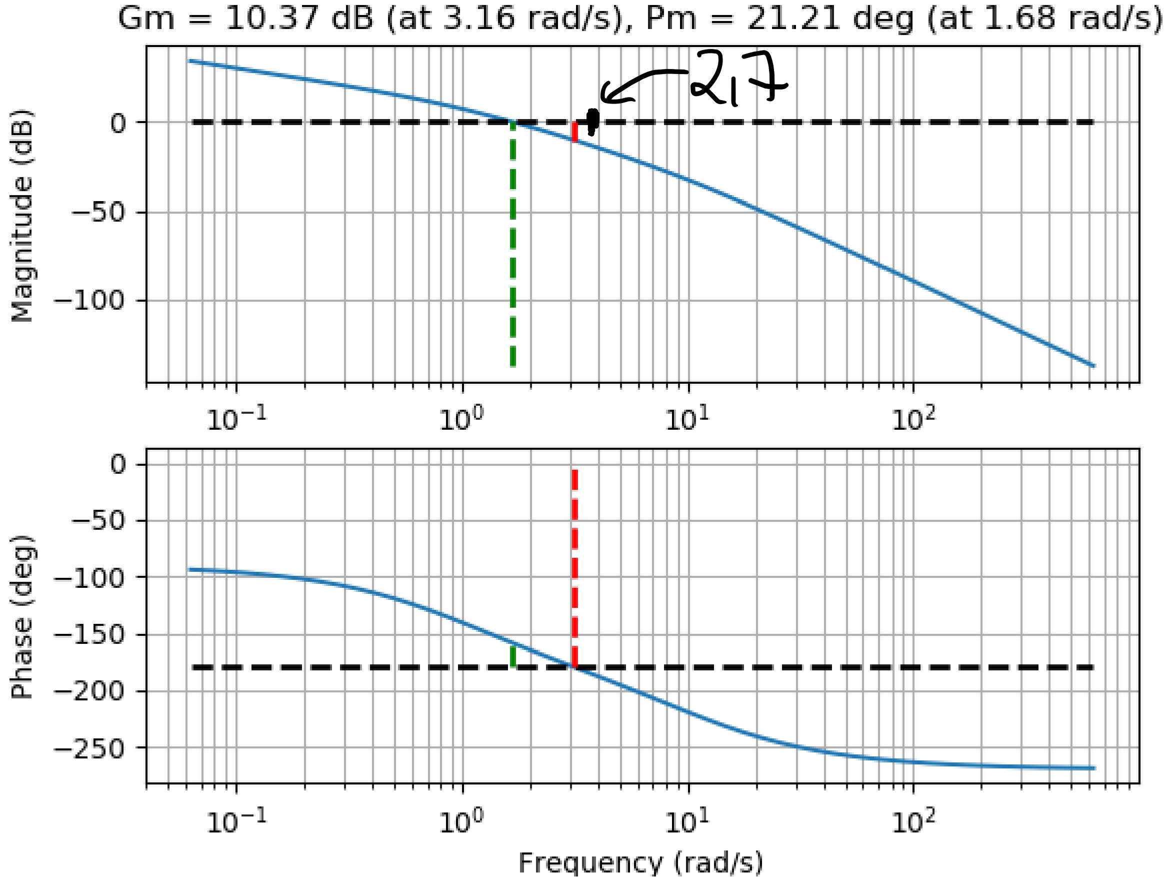
3,33

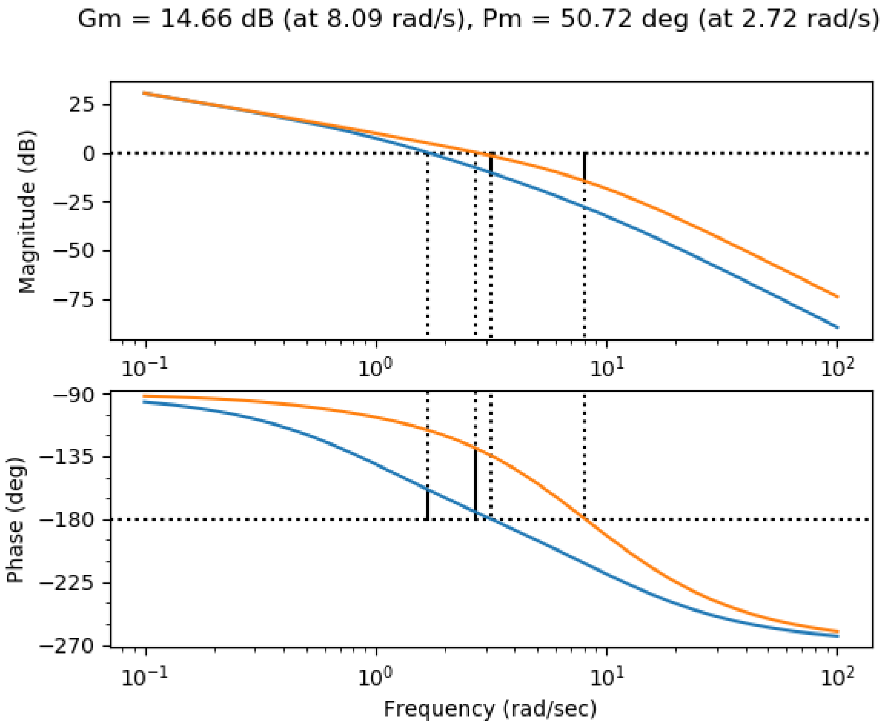
3) NOVA FREQ CRUZAMENTO

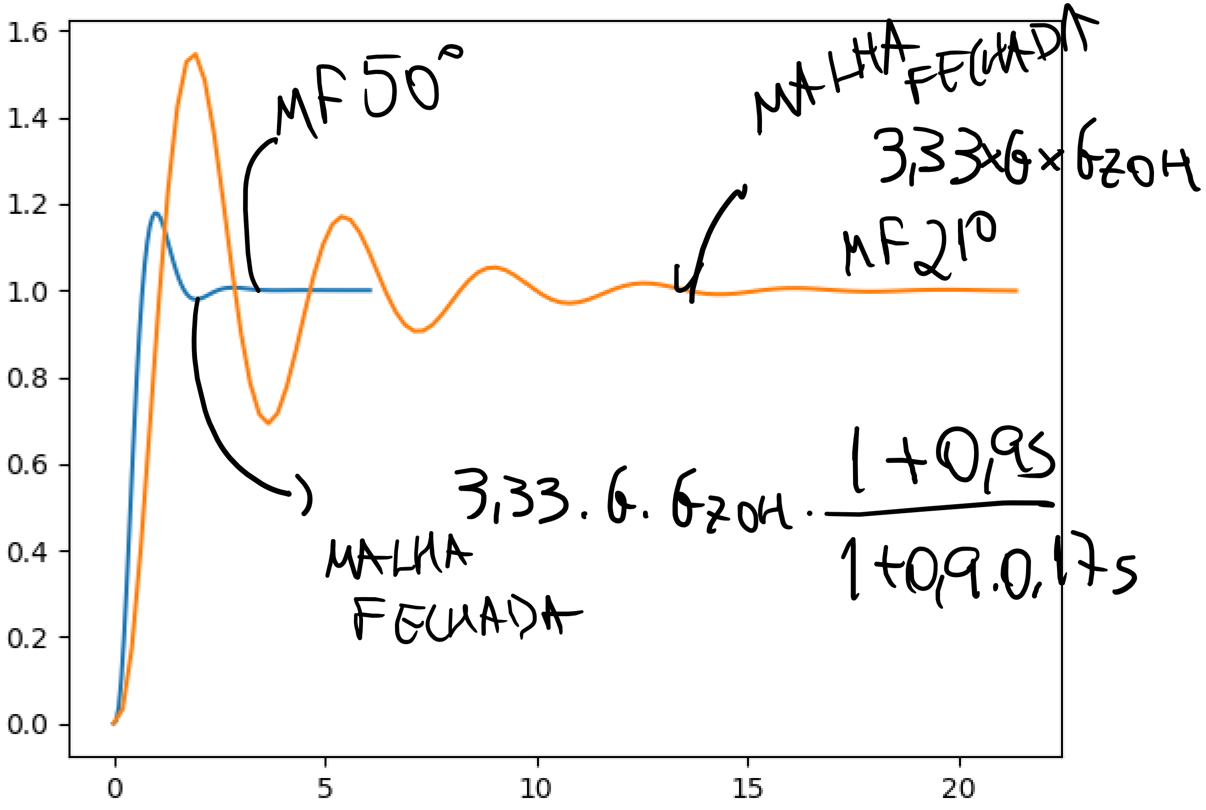
$$|G(w_c)| = -20\log\left(\frac{1}{\sqrt{\alpha}}\right) \rightarrow w_c = 2{,}7\,\text{rad/s}$$

4) OBTER T $\rightarrow w_c = \dfrac{1}{\sqrt{\alpha}\cdot T}$

$\Rightarrow T = 0{,}9$

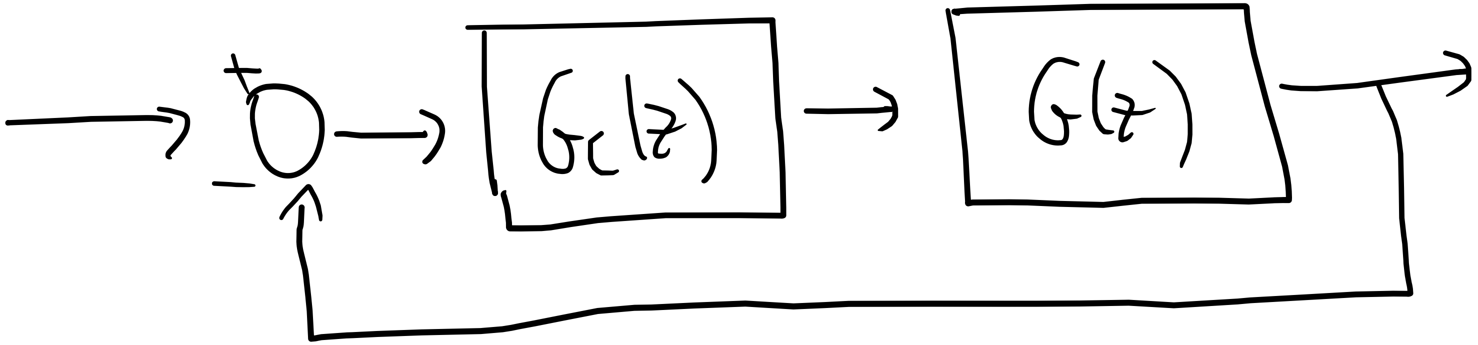






1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
MF 50°
MALHA FECHADA
3,33x6 x G ZOH
MF 21°
MALHA FECHADA
3,33 . 6 . G ZOH . (1+0,9s)/(1+0,9.0,17s)

DIGITALIZAÇÃO



$$G(z) = \mathcal{Z}\left\{ \mathcal{L}^{-1}\left(\frac{G(s)}{s} \right) \right\} \frac{z-1}{z} \rightarrow \text{c2d - 'zoh'} \rightarrow$$

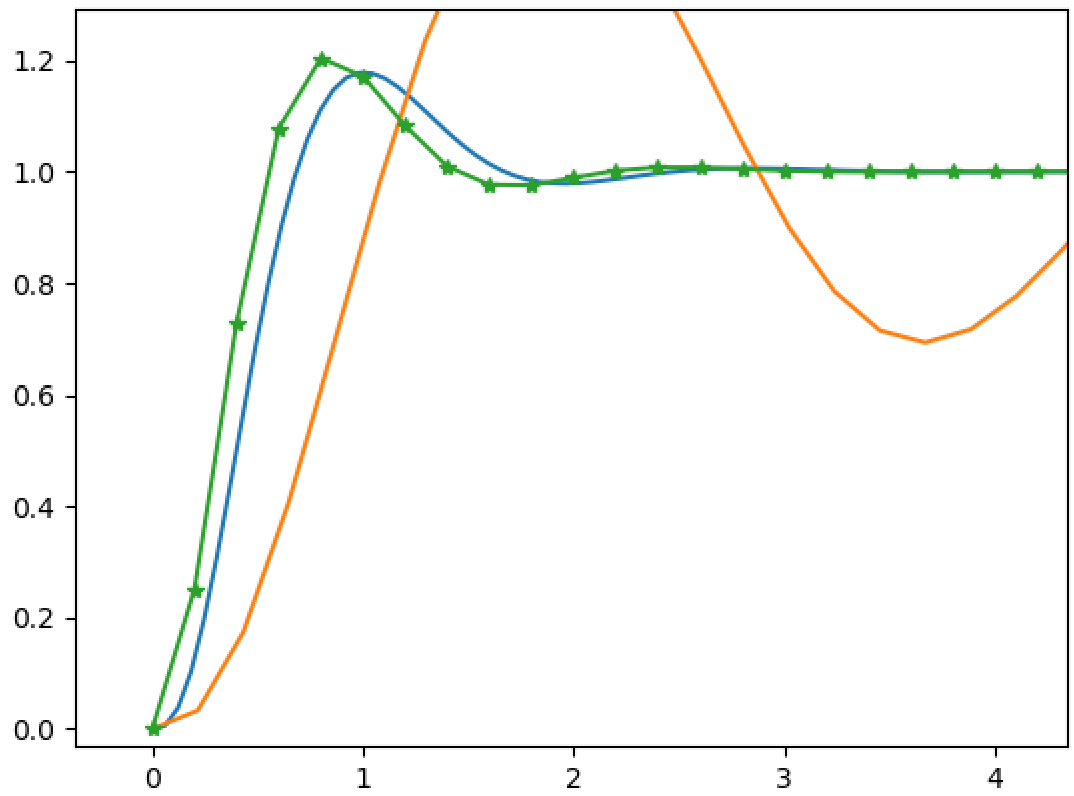
$$\frac{0.01873z + 0.01752}{z^2 - 1.819z + 0.8187} \quad dt = 0.2$$

$$G_c(z) \rightarrow \text{bilinear} \rightarrow s \rightarrow \frac{2}{T}\frac{z-1}{z+1}$$

OU

TUSTIN

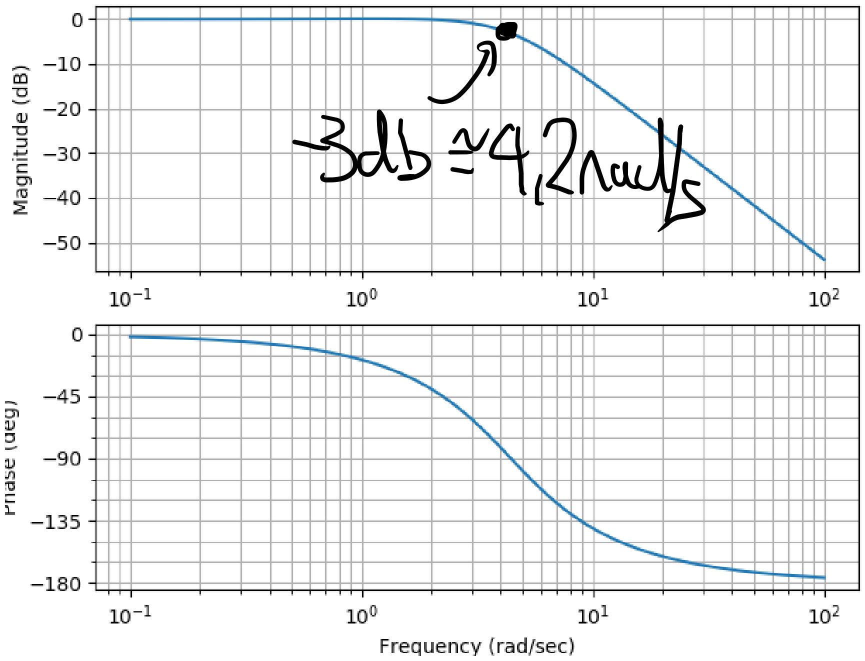
$$\frac{13.42z - 10.74}{z - 0.1957} \quad dt = 0.2$$



COM $T_s = 0{,}2s$, A DEGRADAÇÃO É POUCO IMPORTANTE.

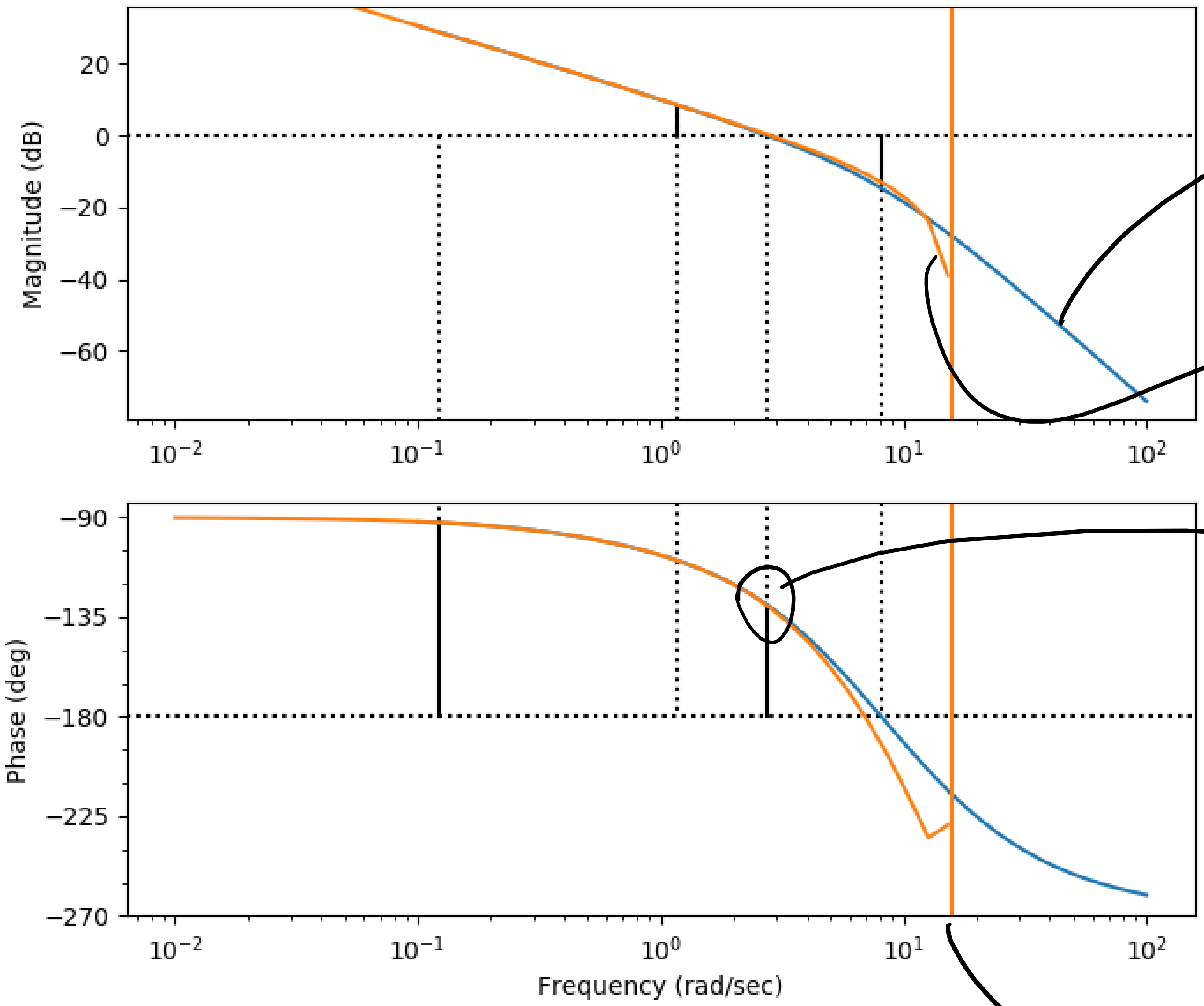
DISCUSSÃO SOBRE T_s

BODE MALHA FECHADA



$$\omega_b = 4{,}2\,rad/s \rightarrow T_s \cong \frac{2\pi}{4{,}2} \cdot \frac{1}{20}$$

$\boxed{T_s = 0{,}07s}$ → FIZEMOS C/ 0,2s (3× MAIO



BODE MALHA ABERTA
CONTÍNUO

BODE M.A. DISCRETO

POUCA DIFERENÇA
MARGEM

$$\frac{2\pi}{2s} \cdot \frac{1}{2} = 1,57 \, rad/s = \omega_N$$

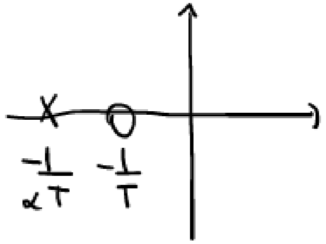
Recapitulação de Projeto de Compensador de Avanço

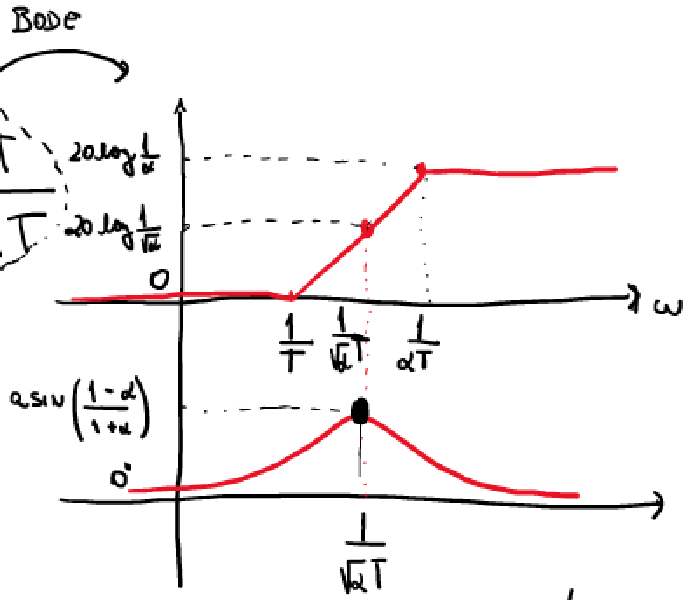
PROJETO DE COMPENSADORES POR RESP. EM FREQ

1) AVANÇO

$$G_c(s) = K_c \cdot \frac{1+sT}{1+\alpha sT}$$

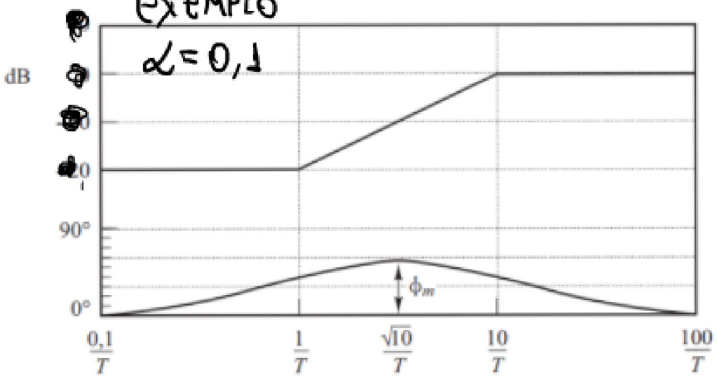
$\alpha < 1$



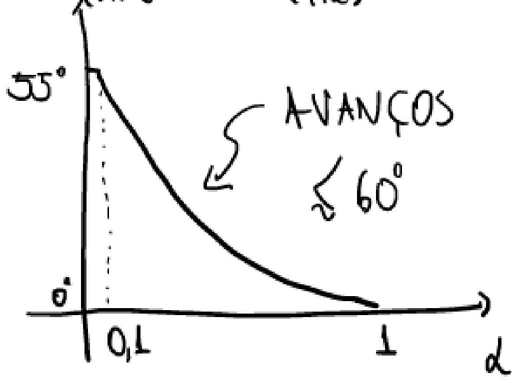


EXEMPLO

$\alpha = 0{,}1$



$$\phi_m = \operatorname{asin}\left(\frac{1-\alpha}{1+\alpha}\right)$$



PROJETO

→ OBJETIVO: AUMENTAR A MARGEM DE FASE NA FREQ. CORTE GANHO $(|G(j\omega_c)| = 1)$

PROCEDIMENTO

ESPECIFICAÇÃO DE ERRO ESTACIONÁRIO E M.F. PROJETAR

$$G_c = K_c \cdot \frac{1+sT}{1+\alpha sT}$$

a) OBTER K_c P/ ATENDER ERRO ESTACIONÁRIO

b) OBTER M.F. P/ SIST. $G_c = K_c$ (SEM COMPENSADOR)

c) OBTER AVANÇO NECESSÁRIO

d) OBTER α $\quad \sin\phi_m = \frac{1-\alpha}{1+\alpha}$

e) OBTER NOVA FREQ. CRUZAMENTO, ONDE GANHO $= -20\log\left(\frac{1}{\sqrt{\alpha}}\right)$

f) OBTER T → $\omega_c = \frac{1}{\sqrt{\alpha}T}$

Ex) $G(s) = \dfrac{4}{s(s+2)}$

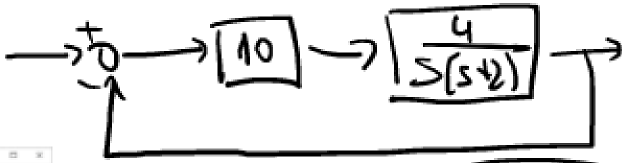
REQ. $\begin{cases} K_v = 20\,\text{seg}^{-1} \\ MF = 50^\circ \end{cases}$

a) $K_v = \lim_{s \to 0} K_c \cdot G(s) \cdot s = 20$

$K_c \dfrac{4}{(\cancel{s}+2)\cancel{s}} \cdot \cancel{s} = 20 \Rightarrow \boxed{K_c = 10}$

b) $G_c(s) = 10 \cdot \dfrac{1+sT}{1+\alpha s T}$

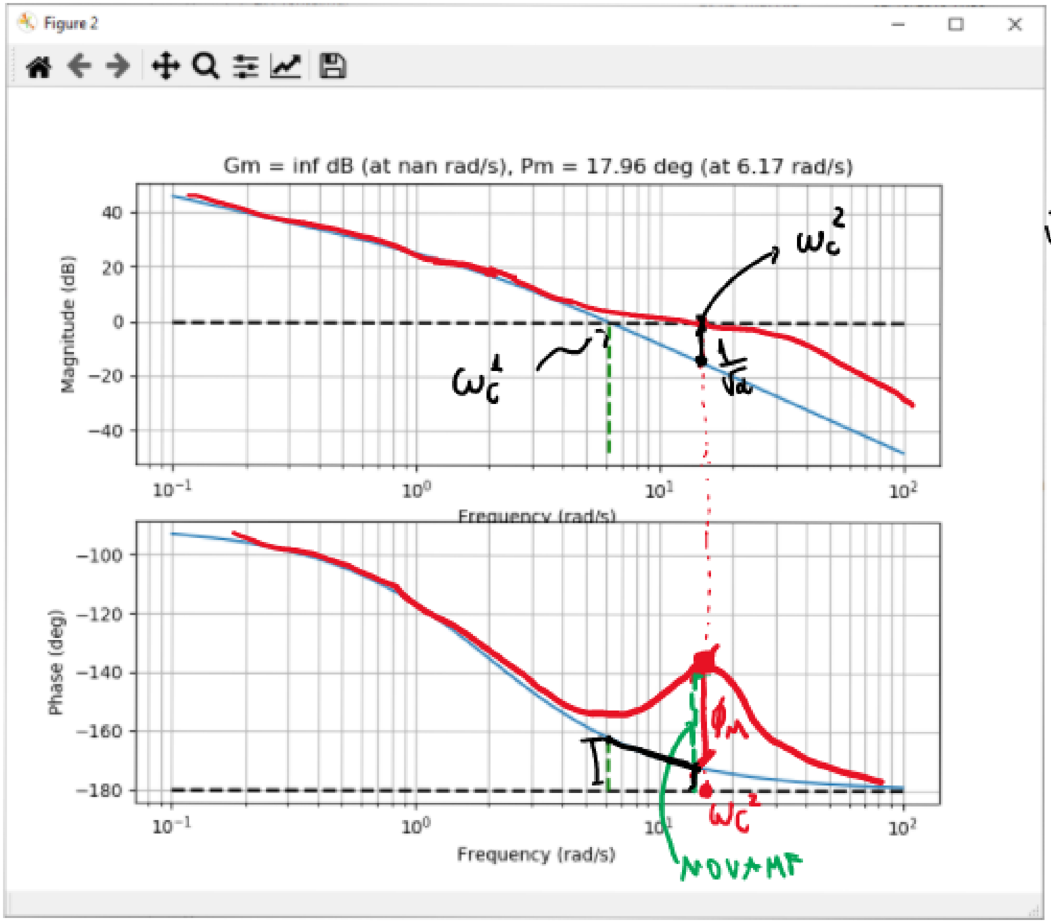
SERÁ QUE APENAS $G_c(s) = 10$ JÁ RESOLVE O PROBLEMA?



c) $\phi_m = 50^\circ - 18^\circ + \overset{5 \sim 10^\circ}{\Delta} = \underline{38^\circ}$

d) $\sin \phi_M = \dfrac{1-\alpha}{1+\alpha} \Rightarrow \boxed{\alpha = 0{,}24}$

e)



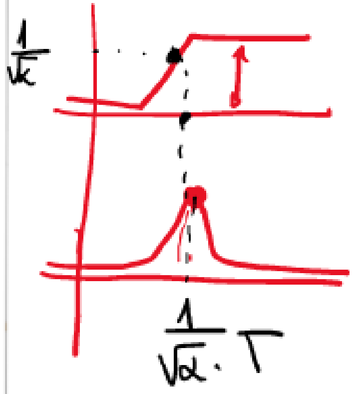
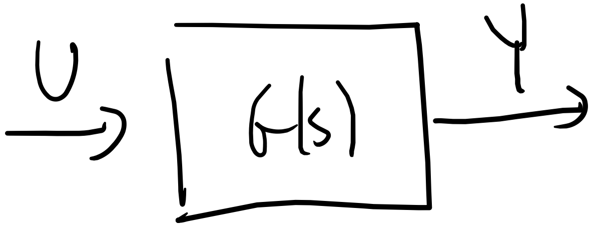


Diagrama de Bode de Sistemas Discretos

BODE $\rightarrow$ $G(s) \rightsquigarrow S = j\omega$

$\hookrightarrow$ MAGNITUDE $\equiv \left|G(j\omega)\right| = \left|\frac{Y}{U}\right|$



$\hookrightarrow$ MUDANÇA FASE $\equiv \angle G(j\omega) = \angle Y - \angle U$

$G(z) \rightsquigarrow z = e^{j\omega T}$

$\hookrightarrow$ MAGNITUDE $= \left|G(e^{j\omega T})\right|$

$\hookrightarrow$ FASE $= \angle G(e^{j\omega T})$

$\rightsquigarrow$ DEIXA DE VALER AS ASSÍNTOTAS DE FORMA NUMÉRICA

Diagrama de Bode de Sistemas Discretos

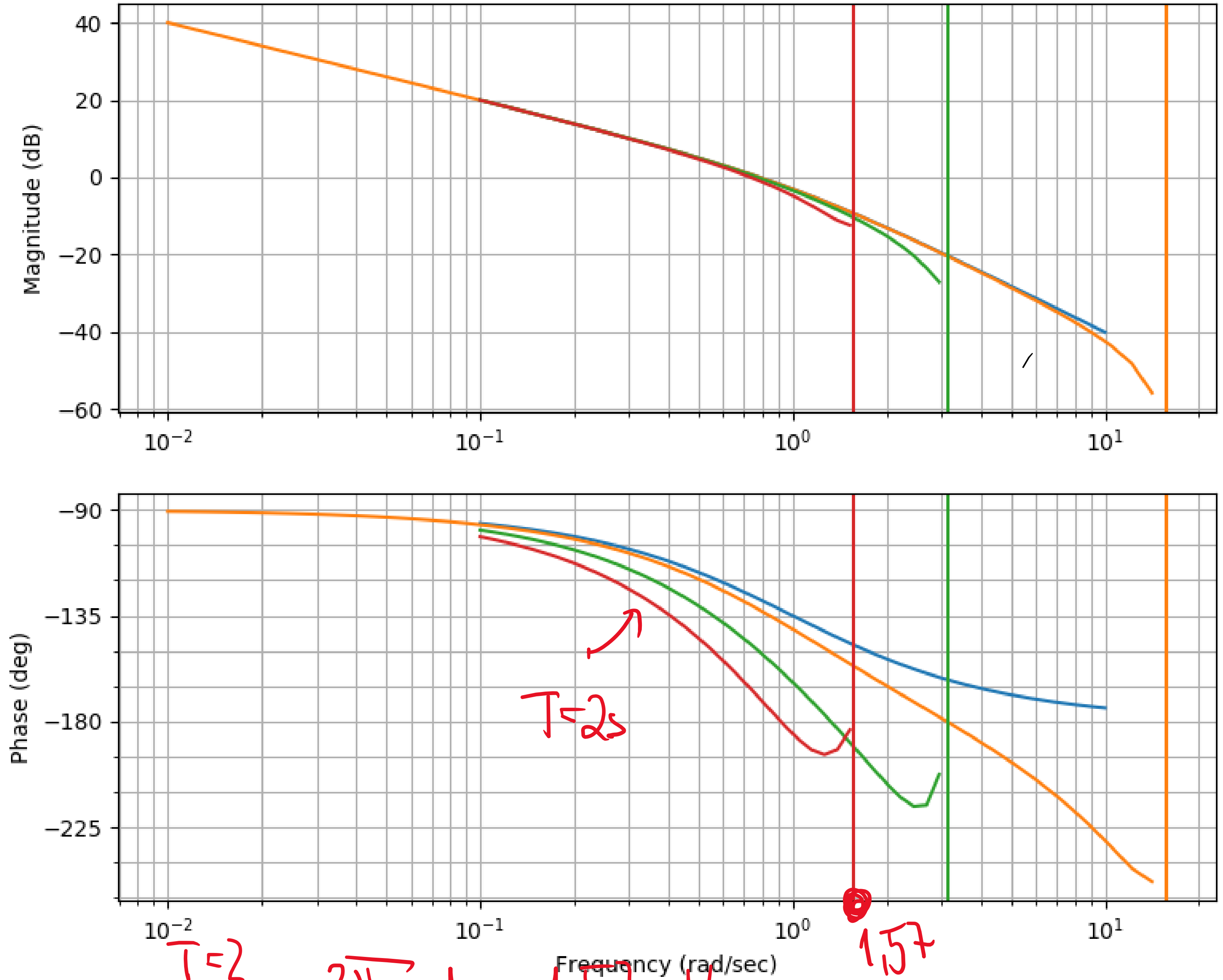
$$G(s) = \frac{1}{s(s+1)}$$ (PLANTA)

↓

$$G(z) = 0{,}0187 \; \frac{z+0{,}935}{(z-1)(z-0{,}819)} \quad T = 0{,}2s$$

$$G(z) = 0{,}368 \cdot \frac{z+0{,}72}{(z-1)(z-0{,}368)} \quad T = 1{,}0s$$

⋮



$$\omega_N^{T=2} = \frac{2\pi}{2}\cdot\frac{1}{2} = 1,57 \text{ rad/s}$$

=> O MÓDULO NÃO MUDA MUITO

=> A DISCRETIZAÇÃO REDUZ MARGEM DE FASE EM $\frac{\omega T}{2}$

$$\Delta\phi = \angle e^{sT/2} = \angle e^{j\omega T/2} = \frac{\omega T}{2}$$