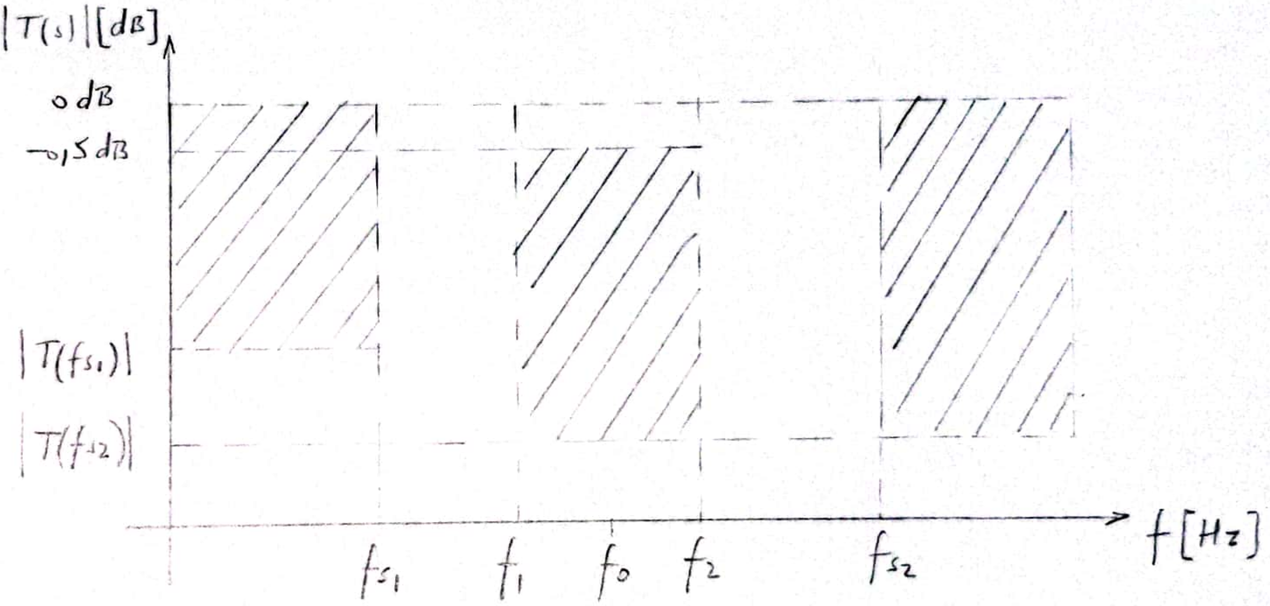
$\omega_0 = 2\pi \, 22 KHz$, $q = 5$

Aproximación Chevyshev con ripple de 0,5 dB

$|T(f_{s_1})| = -16 \, dB$ para $f_{s_1} = 17 \, KHz$

$|T(f_{s_2})| = -24 \, dB$ para $f_{s_2} = 36 \, KHz$



Schaumann: "Lowpass-to-Bandpass Transformation", Cap 9.2, Pág 360-361

1. $\omega_0 = \sqrt{\omega_1 \omega_2}$; $\omega_2 = \dfrac{\omega_0^2}{\omega_1}$ (1) $\qquad \dfrac{\omega_0^2}{\omega_1} = \dfrac{\omega_0}{q} + \omega_1$

$q = \dfrac{\omega_0}{\omega_2 - \omega_1}$; $\omega_2 = \dfrac{\omega_0}{q} + \omega_1$ $\qquad \dfrac{\omega_0^2}{\omega_1} - \omega_1 = \dfrac{\omega_0}{q}$

Multiplico por ω_1 mam: $\omega_0^2 - \omega_1^2 = \dfrac{\omega_0}{q} \omega_1$

$$\omega_1^2 + \frac{\omega_0}{q} \omega_1 - \omega_0^2 = 0$$

$$\omega_1^2 + \frac{2\pi\, 22\,KHz}{5}\,\omega_1 - \left(2\pi\, 22\,KHz\right)^2 = 0$$

$$\omega_1^2 + 8800\pi\left[\frac{rad}{s}\right]\omega_1 - 1{,}936.10^9\,\pi^2\left[\frac{rad}{s}\right]^2 = 0$$

$$\omega_{11} = 125{,}0965.10^3\,\frac{rad}{s} \quad ; \quad \underbrace{\omega_{12} = -\_\_\_\_\_\_\_\_\ \frac{rad}{s}}_{\text{Descartado.}}$$

Reemplazando $\omega_{11} = \omega_1 = 125{,}0965.10^3\,\frac{rad}{s}$ en (1):

$$\omega_2 = \frac{\omega_0^2}{\omega_1} = \frac{(2\pi.\,22\,KHz)^2}{125{,}0965.10^3\,\frac{rad}{s}} = 152{,}7425.10^3\,\frac{rad}{s}$$

2. $\Omega\omega = \omega_0 = 2\pi\, 22\,KHz$

$$\omega_{1-n} = \frac{\omega_1}{\Omega\omega} = \frac{\omega_1}{\omega_0} = \frac{125{,}0965.10^3\,rad/s}{2\pi.\,22\,KHz} \simeq 0{,}9050$$

$$\omega_{2-n} = \frac{\omega_2}{\Omega\omega} = \frac{\omega_2}{\omega_0} = \frac{152{,}7425.10^3\,rad/s}{2\pi.\,22\,KHz} \simeq 1{,}1050$$

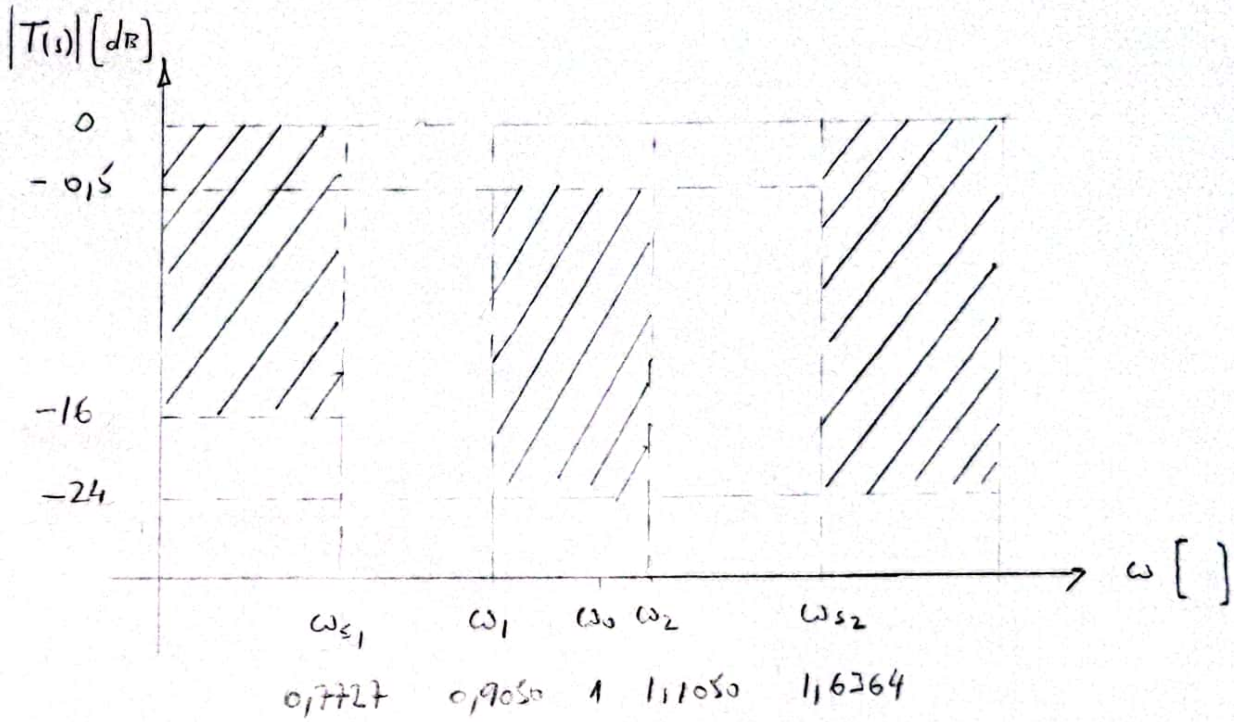
$$\omega_{s_1-n} = \frac{\omega_{s_1}}{\Omega\omega} = \frac{\omega_{s_1}}{\omega_0} = \frac{2\pi.f_{s_1}}{\omega_0} = \frac{\cancel{2\pi}\, 17\,K\cancel{Hz}}{\cancel{2\pi}\, 22\,K\cancel{Hz}} \simeq 0{,}7727$$

$$\omega_{s_2-n} = \frac{\omega_{s2}}{\Omega\omega} = \frac{\omega_{s2}}{\omega_0} = \frac{2\pi\, f_{s2}}{\omega_0} = \frac{\cancel{2\pi}\, 36\,K\cancel{Hz}}{\cancel{2\pi}\, 22.\,K\cancel{Hz}} \simeq 1{,}6364$$

$$\omega_{0-n} = \frac{\omega_0}{\Omega\omega} = \frac{\omega_0}{\omega_0} = 1$$

En adelante, omito el subíndice n pero recordando que se trata de pulsaciones (o bien frecuencias) normalizadas.

Plantilla de diseño pasabanda normalizada:



3.

$$\Omega_{s_1} = q\,\frac{(\omega_{s_1}^2 - 1)}{\omega_{s_1}} = 5\,\frac{(0{,}7727^2 - 1)}{0{,}7727} = -2{,}6073$$

Como $|T_{LP}|$ se trata de una función par, desestimamos el signo (−).

$$\Omega_{s_2} = q\,\frac{(\omega_{s_2}^2 - 1)}{\omega_{s_2}} = 5\,\frac{(1{,}6364^2 - 1)}{1{,}6364} = 5{,}1265$$

5. $$|T_{LP}(j\Omega)|^2 = T_{LP}(j\Omega) \cdot T_{LP}(-j\Omega) = T_{LP}(s)\, T_{LP}(-s)\Big|_{s=j\Omega}$$

$$= \frac{1}{1+\xi^2 C_n^2(\Omega)}$$

$$|\alpha|^2 = 1+\xi^2 C_n^2(\Omega) \; ; \; |\alpha|_{dB} \triangleq \alpha_{dB} \; ;$$

$$\alpha_{dB} = 10 \log\left[1+\xi^2 C_n^2(\Omega)\right]$$

Despejando ξ^2 : $\xi^2 = \dfrac{10^{\alpha dB/10} - 1}{C_n^2(\Omega)}$

Para $(\alpha_{máx}, f_p)$, o bien, $(\alpha_{máx}, \Omega_{p_n})$, obtengo ξ^2:

$$\xi^2 = \frac{10^{\alpha_{máx}/10} - 1}{C_n^2(\Omega_{p_n})} = \frac{10^{0{,}5/10} - 1}{1} = 0{,}122 \; ; \; \xi = 0{,}3493$$

Para $(\alpha_{mín}, f_{s_1})$, o bien, $(\alpha_{mín}, \Omega_{s_1})$, itero n veces hasta encontrar un $n \in \mathbb{Z}$ que cumpla con $\alpha_{mín} \geq 16\,dB$:

$$\alpha_{mín}\, dB = 10 \log\left[1+\xi^2 C_n^2(\Omega_{s_1})\right]$$

$$\alpha_{mín}\, dB = 10 \log\left\{1+\xi^2 \cosh^2\left[n \cdot \cosh^{-1}(\Omega_{s_1})\right]\right\}$$

$n=1 \; : \; \alpha_{mín}\, dB = 10 \log \left\{ 1 + 0{,}122 \cosh^2 \left[1 \cdot \cosh^{-1}(2{,}6073) \right] \right\}$

$= 2{,}623 \text{ dB}$

$n=2 \; : \; \alpha_{mín}\, dB = 10 \log \left\{ 1 + 0{,}122 \cosh^2 \left[2 \cdot \cosh^{-1}(2{,}6073) \right] \right\}$

$= 13{,}088 \text{ dB}$

$n=3 \; : \; \alpha_{mín}\, dB = 10 \log \left\{ 1 + 0{,}122 \cosh^2 \left[3 \cdot \cosh^{-1}(2{,}6073) \right] \right\}$

$= 26{,}870 \text{ dB} \geq 16 \text{ dB}$

Para $(\alpha_{mín}, f_{s_2})$, o bien, $(\alpha_{mín}, \Omega_{s_2})$, itero n veces hasta encontrar un $n \in \mathbb{Z}$ que cumpla con $\alpha_{mín} \geq 24$ dB:

$\alpha_{mín}\, dB = 10 \log \left\{ 1 + \xi^2 \cosh^2 \left[n \cdot \cosh^{-1}(\Omega_{s_2}) \right] \right\}$

$n=1 \; : \; \alpha_{mín}\, dB = 10 \log \left\{ 1 + 0{,}122 \cosh^2 \left[1 \cdot \cosh^{-1}(5{,}1265) \right] \right\}$

$= 6{,}239 \text{ dB}$

$n=2 \; : \; \alpha_{mín}\, dB = 10 \log \left\{ 1 + 0{,}122 \cosh^2 \left[2 \cdot \cosh^{-1}(5{,}1265) \right] \right\}$

$= 25{,}124 \text{ dB} \geq 24 \text{ dB}$

Nos quedamos con $n=3$ de forma que satisfaga ambos requerimientos.

6. $C_0(\Omega) = 1$

$C_1(\Omega) = \Omega$

$C_n(\Omega) = 2\Omega \cdot C_{n-1}(\Omega) - C_{n-2}(\Omega)$

$C_2(\Omega) = 2\Omega \cdot \Omega - 1 = 2\Omega^2 - 1$

$C_3(\Omega) = 2\Omega(2\Omega^2-1) - \Omega = 4\Omega^3 - 2\Omega - \Omega = 4\Omega^3 - 3\Omega$

$$|T_{LP}(j\Omega)|^2 = \frac{1}{1+\xi^2 C_3^2(\Omega)} = \frac{1}{1+\xi^2(4\Omega^3-3\Omega)^2}$$

$$= \frac{1}{1+\xi^2(4\Omega^3-3\Omega)(4\Omega^3-3\Omega)}$$

$$= \frac{1}{1+\xi^2(16\Omega^6-12\Omega^4-12\Omega^4+9\Omega^2)}$$

$$= \frac{1}{16\xi^2\Omega^6-24\xi^2\Omega^4+9\xi^2\Omega^2+1}$$

Divido numerador y denominador por $16\xi^2$:

$$\left|T_{LP}(j\Omega)\right|^2 = \frac{a}{\Omega^6 - b\,\Omega^4 + c\,\Omega^2 + a} \quad ; \quad b = \frac{24\,\xi^2}{16\,\xi^2} = \frac{3}{2}$$

$$c = \frac{9\,\xi^2}{16\,\xi^2} = \frac{9}{16}$$

Reemplazo Ω por $\frac{s}{j}$:

$$a = \frac{1}{16\,\xi^2}$$

$$\left|T_{LP}(s)\right|^2 = \frac{a}{\left(\frac{s}{j}\right)^6 - b\left(\frac{s}{j}\right)^4 + c\left(\frac{s}{j}\right)^2 + a}$$

$$= \frac{a}{-s^6 - b\,s^4 - c\,s^2 + a}$$

$$\left|T_{LP}(s)\right|^2 = T_{LP}(s)\,.\,T_{LP}(-s) = \underbrace{\frac{\alpha}{s^3 + \beta\,s^2 + \gamma\,s + \alpha}}_{T_{LP}(s)}\ \underbrace{\frac{\alpha}{-s^3 + \beta\,s^2 - \gamma\,s + \alpha}}_{T_{LP}(-s)}$$

$$= \frac{\alpha^2}{-s^6 + \beta s^5 - \gamma s^4 + \alpha s^3 - \beta s^5 + \beta^2 s^4 - \beta\gamma s^3 + \alpha\beta s^2 \rightarrow}$$

$$\rightarrow - \gamma s^4 + \beta\gamma s^3 - \gamma^2 s^2 + \alpha\gamma s - \alpha s^3 + \alpha\beta s^2 - \alpha\gamma s + \alpha^2$$

$$= \frac{\alpha^2}{-s^6 + (\beta - \beta)s^5 + (-\gamma + \beta^2 - \gamma)s^4 + (\alpha - \beta\gamma + \beta\gamma - \alpha)s^3 + (\alpha\beta - \gamma^2 + \alpha\beta)s^2 + (\alpha\gamma - \alpha\gamma)s + \alpha^2}$$

$$= \frac{\alpha^2}{-s^6 + \underbrace{(\beta^2 - 2\gamma)}_{-b} s^4 + \underbrace{(2\alpha\beta - \gamma^2)}_{-c} s^2 + \underbrace{\alpha^2}_{a}}$$

$$a = \alpha^2 = \frac{1}{16\xi^2} \; ; \; \alpha = \frac{1}{4\xi} = \frac{1}{4 \cdot 0{,}3493} = 0{,}7157$$

$$-b = \beta^2 - 2\gamma = -\frac{3}{2} \; ; \; \beta = \sqrt{2\gamma - \frac{3}{2}} \; ; \; \gamma = \frac{\beta^2}{2} + \frac{3}{4} \quad (1)$$

$$-c = 2\alpha\beta - \gamma^2 = -\frac{9}{16} \; ; \; \gamma = \sqrt{2\alpha\beta + \frac{9}{16}} \; ; \; \beta = \frac{\gamma^2}{2\alpha} - \frac{9}{32\alpha}$$

$$\gamma = \sqrt{2 \cdot 0{,}7157 \cdot \beta + \frac{9}{16}} \; ; \; \beta = \frac{\gamma^2}{2 \cdot 0{,}7157} - \frac{9}{32 \cdot 0{,}7157}$$

$$\gamma = \sqrt{1{,}4314\beta + \frac{9}{16}} \quad (3) \; ; \; \beta = \frac{\gamma^2}{1{,}4314} - 0{,}3930 \quad (2)$$

Reemplazo (1) en (2):

$$\beta = \frac{\left(\frac{\beta^2}{2}+\frac{3}{4}\right)^2}{1,4314} - 0,3930 = \frac{\left(\frac{\beta^4}{4} + \cancel{2}\frac{\beta^2}{\cancel{2}}\frac{3}{4} + \frac{9}{16}\right)}{1,4314} - 0,3930$$

$$\beta = 0,6986\left(\frac{\beta^4}{4} + \frac{3\beta^2}{4} + \frac{9}{16}\right) - 0,3930 =$$

$$0,6986\,\frac{\beta^4}{4} + 0,6986\,\frac{3\beta^2}{4} - \beta + 0,6986\,\frac{9}{16} - 0,3930 =$$

$$0,1747\,\beta^4 + 0,5239\,\beta^2 - \beta + \cancel{0,3930} - \cancel{0,3930} =$$

$$\beta^4 + 2,9988\,\beta^2 - 5,7241\,\beta = 0 \;;\; \beta\left(\beta^3 + 2,9988\,\beta - 5,7241\right) = 0$$

$\beta_1 = 0$, $\underline{\beta_2 = 1,2529}$, β_3, β_4, raíces complejas conjugadas

Reemplazando $\beta_2 = \beta$ en (1):

$$\gamma = \frac{1,2529^2}{2} + \frac{3}{4} = 1,5349$$

Verificación: $\beta^2 - 2\gamma = -b$; $1,2529^2 - 2 . 1,5349 = -\frac{3}{2}$ ✓

$2\alpha\beta - \gamma^2 = -c$; $2 . 0,7157 . 1,2529 - 1,5349^2 = -\frac{9}{16}$ ✓

$$T_{LP}(s) = \frac{\alpha}{s^3 + \beta s^2 + \gamma s + \alpha} = \frac{0,7157}{s^3 + 1,2529\, s^2 + 1,5349\, s + 0,7157}$$

7. $$T_{LP}(\not s)\Big|_{\not s = K(s) = \frac{1}{B}\frac{s^2+1}{s}} = T_{BP}(s)$$

Reemplazando el núcleo de la transformación $K(s)$ en $T_{LP}(\not s)$:

$$T_{BP}(s) = \frac{0,7157}{\left(\frac{1}{B}\frac{s^2+1}{s}\right)^3 + 1,2529\left(\frac{1}{B}\frac{s^2+1}{s}\right)^2 + 1,5349\left(\frac{1}{B}\frac{s^2+1}{s}\right) + 0,7157}$$

$$= \frac{0,7157}{\frac{1}{B^3}\frac{(s^2+1)^3}{s^3} + 1,2529\,\frac{1}{B^2}\frac{(s^2+1)^2}{s^2} + 1,5349\,\frac{1}{B}\frac{s^2+1}{s} + 0,7157}$$

$$= \frac{0,7157}{\frac{(s^2+1)(s^2+1)(s^2+1)}{B^3 s^3} + 1,2529\,\frac{1}{B^2}\frac{s^4+2s^2+1}{s^2} + 1,5349\,\frac{1}{B}\frac{s^2+1}{s} + 0,7157}$$

$$= \frac{0,7157}{\frac{(s^4+2s^2+1)(s^2+1)}{B^3 s^3} + \ldots}$$

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$$= \cfrac{0{,}7157}{\cfrac{s^6+s^4+2s^4+2s^2+s^2+1}{B^3 s^3} + \cdots}$$

$$= \cfrac{0{,}7157}{\cfrac{s^6+3s^4+3s^2+1}{B^3 s^3} + \cfrac{1{,}2529\,(s^4+2s^2+1)}{B^2 s^2} + \cfrac{1{,}5349\,(s^2+1)}{B.s} + 0{,}7157}$$

$$= \cfrac{0{,}7157}{\cfrac{s^6+3s^4+3s^2+1 + \left[1{,}2529\,(s^4+2s^2+1)\,Bs\right] + \left[1{,}5349\,(s^2+1)\,B^2s^2\right] + 0{,}7157\,B^3s^3}{B^3 s^3}}$$

$$= \frac{0{,}7157\,B^3s^3}{s^6+3s^4+3s^2+1+\left[1{,}2529\,(s^4+2s^2+1)\,Bs\right]+\left[1{,}5349\,(s^2+1)\,B^2s^2\right]+0{,}7157\,B^3s^3}$$

$$= \frac{0{,}7157\,B^3s^3}{s^6+3s^4+3s^2+1+1{,}2529.Bs^5+2{,}5058.Bs^3+1{,}2529.Bs+1{,}5349\,B^2s^4+1{,}5349\,B^2s^2+0{,}7157\,B^3s^3}$$

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$$= \frac{0{,}7157\, B^3 s^3}{s^6 + 1{,}2529\, B\, s^5 + \left(3 + 1{,}5349\, B^2\right) s^4 + \left(2{,}5058 \cdot B + 0{,}7157\, B^3\right) s^3 + \left(3 + 1{,}5349\, B^2\right) s^2 + 1{,}2529\, B\, s + 1}$$

$$= \frac{0{,}7157 \cdot \left(\frac{1}{5}\right)^3 s^3}{s^6 + 1{,}2529 \cdot \frac{1}{5}\, s^5 + \left[3 + 1{,}5349 \left(\frac{1}{5}\right)^2\right] s^4 + \left[2{,}5058\, \frac{1}{5} + 0{,}7157 \left(\frac{1}{5}\right)^3\right] s^3 + \left[3 + 1{,}5349 \left(\frac{1}{5}\right)^2\right] s^2 + 1{,}2529\, \frac{1}{5}\, s + 1}$$

$$= \frac{5{,}7256 \cdot 10^{-3}\, s^3}{\underbrace{s^6 + 0{,}2506\, s^5 + 3{,}0614\, s^4 + 0{,}5069\, s^3 + 3{,}0614\, s^2 + 0{,}2506\, s + 1}_{den}}$$

raices_den = numpy.roots(den)

$p_1 = -0{,}0347 + j1{,}1069 \qquad p_4 = -0{,}0624 - j0{,}9981$

$p_2 = -0{,}0347 - j1{,}1069 \qquad p_5 = -0{,}0283 + j0{,}9026$

$p_3 = -0{,}0624 + j0{,}9981 \qquad p_6 = -0{,}0283 - j0{,}9026$

$$T_{BP}(s) = \frac{5{,}7256\cdot 10^{-3}\, s^3}{(s-p_1)(s-p_2)(s-p_3)(s-p_4)(s-p_5)(s-p_6)}$$

$$T_{BP}(s) = \frac{5{,}7256\cdot 10^{-3}\, s^3}{\left[s-(-0{,}0347+j1{,}1069)\right]\left[s-(-0{,}0347-j1{,}1069)\right] \rightarrow}$$

$$\rightarrow \left[s-(-0{,}0624+j0{,}9981)\right]\left[s-(-0{,}0624-j0{,}9981)\right] \rightarrow$$

$$\rightarrow \left[s-(-0{,}0283+j0{,}9026)\right]\left[s-(-0{,}0283-j0{,}9026)\right]$$

$$T_{BP}(s) = \frac{5{,}7256\cdot 10^{-3}\, s^3}{\left(s^2+0{,}0347s+j1{,}1069s+0{,}0347s+0{,}0347^2+\right. \rightarrow}$$

$$\rightarrow \left. j0{,}0347\cdot 1{,}1069 - j1{,}1069s - j1{,}1069\cdot 0{,}0347 - j^2 1{,}1069^2\right) \rightarrow$$

$$\rightarrow \left(s^2+0{,}0624s+j0{,}9981s+0{,}0624s+0{,}0624^2+\right. \rightarrow$$

$$\rightarrow \left. j0{,}0624\cdot 0{,}9981 - j0{,}9981s - j0{,}9981\cdot 0{,}0624 - j^2 0{,}9981^2\right) \rightarrow$$

$$\rightarrow \left(s^2+0{,}0283s+j0{,}9026s+0{,}0283s+0{,}0283^2+\right. \rightarrow$$

$$\rightarrow \left. j0{,}0283\cdot 0{,}9026 - j0{,}9026s - j0{,}9026\cdot 0{,}0283 - j^2 0{,}9026^2\right)$$

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$$T_{BP}(s) = \frac{5{,}7256 \cdot 10^{-3}\, s^3}{\left[s^2 + (0{,}0347 + 0{,}0347)\, s + 0{,}0347^2 + 1{,}1069^2\right]} \rightarrow$$

$$\frac{}{\left[s^2 + (0{,}0624 + 0{,}0624)\, s + 0{,}0624^2 + 0{,}9981^2\right]} \rightarrow$$

$$\frac{}{\left[s^2 + (0{,}0283 + 0{,}0283)\, s + 0{,}0283^2 + 0{,}9026^2\right]}$$

$$T_{BP}(s) = \frac{5{,}7256 \cdot 10^{-3}\, s^3}{\left(s^2 + 0{,}0694\, s + 1{,}2264\right)\left(s^2 + 0{,}1248\, s + 1\right)} \rightarrow$$

$$\rightarrow \frac{}{\left(s^2 + 0{,}0566\, s + 0{,}8155\right)}$$

$$T_{BP}(s) = \frac{k_1 \frac{\omega_{01}}{q_1} s}{s^2 + \frac{\omega_{01}}{q_1} s + \omega_{01}^2} \quad \frac{k_2 \frac{\omega_{02}}{q_2} s}{s^2 + \frac{\omega_{02}}{q_2} s + \omega_{02}^2} \quad \frac{k_3 \frac{\omega_{03}}{q_3} s}{s^2 + \frac{\omega_{03}}{q_3} s + \omega_{03}}$$

$\omega_{01}^2 = 1{,}2264$	$\omega_{02}^2 = 1$	$\omega_{03}^2 = 0{,}8155$
$\omega_{01} = 1{,}1074$	$\omega_{02} = 1$	$\omega_{03} = 0{,}9031$
$\frac{\omega_{01}}{q_1} = 0{,}0694$	$\frac{\omega_{02}}{q_2} = 0{,}1248$	$\frac{\omega_{03}}{q_3} = 0{,}0566$
$q_1 = 15{,}9568$	$q_2 = 8{,}0128$	$q_3 = 15{,}9558$

$$T_{BP}(s)=\frac{k_1\,\frac{1,1074}{15,9568}\,s}{s^2+\frac{1,1074}{15,9568}\,s+1,2264}\;\frac{k_2\,\frac{1}{8,0128}\,s}{s^2+\frac{1}{8,0128}\,s+1}\;\frac{k_3\,\frac{0,9031}{15,9588}\,s}{s^2+\frac{0,9031}{15,9558}\,s+0,8155}$$

$$k_1\,\frac{1,1074}{15,9568}=k_1\,0,0694=\sqrt[3]{5,7256.10^{-3}}\;;\;k_1=2,5778$$

$$k_2\,\frac{1}{8,0128}=k_2\,0,1248=\sqrt[3]{5,7256.10^{-3}}\;;\;k_2=1,4335$$

$$k_3\,\frac{0,9031}{15,9588}=k_3\,0,0566=\sqrt{5,7256.10^{-3}}\;;\;k_3=3,1608$$

$$T_{BP}(s)=\frac{2,5778.0,0694.s}{s^2+0,0694s+1,2264}\;\frac{1,4335.0,1248\,s}{s^2+0,1248s+1}\;\frac{3,1608.0,0566.s}{s^2+0,0566s+0,8155}$$

Conviene reescribirla como:

$$T_{BP}(s)=\frac{1,4335.0,1248s}{s^2+0,1248s+1}\;\frac{2,5578.0,0694\,s}{s^2+0,0694s+1,2264}\;\frac{3,1608.0,0566\,s}{s^2+0,0566\,s+0,8155}$$

$$=\frac{1,4335\,\frac{1}{8,0128}\,s}{s^2+\frac{1}{8,0128}\,s+1}\;\underbrace{\frac{2,5578.\frac{1,1074}{15,9568}\,s}{s^2+\frac{1,1074}{15,9568}\,s+1,2264}\;\frac{3,1608\,\frac{0,9031}{15,9588}\,s}{s^2+\frac{0,9031}{15,9588}\,s+0,8155}}_{\omega_{01}\cdot\omega_{03}=1\;\wedge\;q_1\simeq q_3}$$

Escaneado con CamScanner