$$T(s) = \frac{U_{iz}(s)}{U_{ul}(s)} = ?$$

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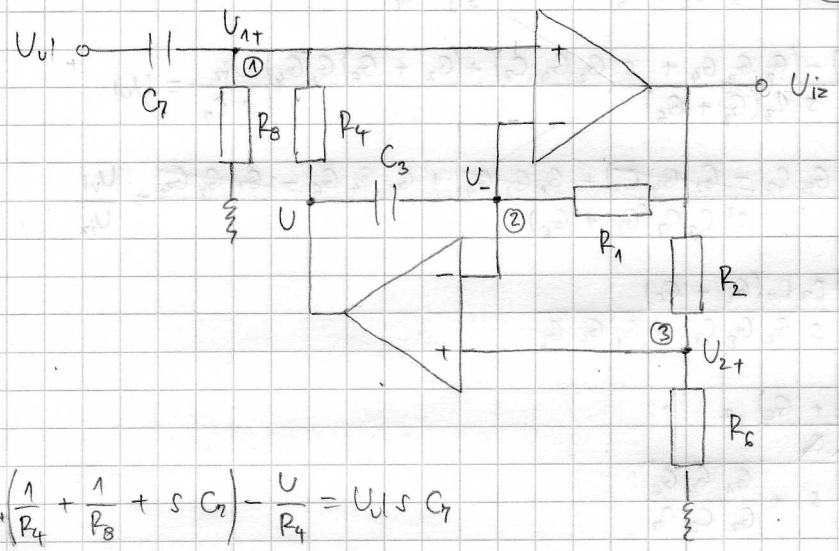


$$U_{1+}\left(\frac{1}{R_4} + \frac{1}{R_8} + s\,C_7\right) - \frac{U}{R_4} = U_{ul}\,s\,C_7$$

$$U_-\left(\frac{1}{R_1} + s\,C_3\right) - U\,s\,C_3 = \frac{U_{iz}}{R_1}$$

$$U_{2+}\left(\frac{1}{R_2} + \frac{1}{R_6}\right) = \frac{U_{iz}}{R_2}$$

$$U_{1+} = U_- = U_{2+} = U_1, \qquad U = U_2$$

$$U_1\left(G_4 + G_8 + s\,C_7\right) = U_{ul}\,s\,C_7 + U_2\,G_4 \qquad (1)$$

$$U_1\left(G_1 + s\,C_3\right) = U_{iz}\,G_1 + U_2\,s\,C_3 \qquad (2)$$

$$U_1\left(G_2 + G_6\right) = U_{iz}\,G_2 \qquad (3)$$

$$U_1 = \frac{G_2}{G_2 + G_6}\,U_{iz} \qquad (3)$$

$$\frac{G_2}{G_2 + G_6}\,U_{iz}\left(G_4 + G_8 + s\,C_7\right) = U_{ul}\,s\,C_7 + U_2\,G_4 \qquad (3) \to (1) \quad (\mathrm{I})$$

$$\frac{G_2}{G_2 + G_6}\,U_{iz}\left(G_1 + s\,C_3\right) = U_{iz}\,G_1 + U_2\,s\,C_3 \qquad (3) \to (2) \quad (\mathrm{II})$$

$$\left[\frac{G_2}{G_2 + G_6}\left(G_1 + s\,C_3\right) - G_1\right]\frac{U_{iz}}{s\,C_3} = U_2 \qquad (\mathrm{II})$$

$$\frac{G_2}{G_2 + G_6}\,U_{iz}\left(G_4 + G_8 + s\,C_7\right) = U_{ul}\,s\,C_7 + \frac{G_4}{s\,C_3}\,U_{iz} \qquad (\mathrm{II}) \to (\mathrm{I})$$

$$\left[\frac{G_2}{G_2+G_6}(G_4+G_8+sC_7)-\frac{G_4}{sC_3}\left[\frac{G_2}{G_2+G_6}(G_1+sC_3)-G_1\right]\right]\frac{U_{iz}}{sC_7}=U_{u1}$$

$$\left[\frac{G_2G_4+G_2G_8+sG_2C_7}{G_2+G_6}-\frac{G_1G_2G_4+sG_2G_4C_3}{sC_3(G_2+G_6)}+\frac{G_1G_4}{sC_3}\right]\frac{U_{iz}}{sC_7}=U_{u1}$$

$$\left[\frac{sC_3(G_2G_4+G_2G_8+sG_2C_7)-(G_1G_2G_4+sG_2G_4C_3)+(G_2+G_6)G_1G_4}{sC_3(G_2+G_6)}\right]\frac{U_{iz}}{sC_7}=U_{u1}$$

$$\frac{s^2G_2C_3C_7+s(\cancel{G_2G_4C_3}+G_2G_8C_3-\cancel{G_2G_4C_3})+\cancel{G_1G_2G_4}+G_1G_4G_6-\cancel{G_1G_2G_4}}{s^2C_3C_7(G_2+G_6)}=\frac{U_{u1}}{U_{iz}}$$

$$T_{VP}(s)=\frac{U_{iz}(s)}{U_{u1}(s)}=\frac{s^2C_3C_7(G_2+G_6)}{s^2G_2C_3C_7+sG_2G_8C_3+G_1G_4G_6}$$

$$T_{VP}(s)=\frac{U_{iz}(s)}{U_{u1}(s)}=\frac{\frac{\cancel{G_2}\cancel{C_3}\cancel{C_7}(G_2+G_6)}{G_2\cancel{C_3}\cancel{C_7}}s^2}{s^2+\frac{\cancel{G_2}G_8\cancel{C_7}}{\cancel{G_2}\cancel{C_3}C_7}s+\frac{G_1G_4G_6}{G_2C_3C_7}}$$

$$T_{VF}(s)=\frac{U_{iz}(s)}{U_{u1}(s)}=\frac{\frac{G_2+G_6}{G_2}s^2}{s^2+\frac{G_8}{C_7}s+\frac{G_1G_4G_6}{G_2C_3C_7}}$$

$K=?$, $Q_p=?$, $\omega_p=?$

$$T(s)=\frac{Ks^2}{s^2+\frac{\omega_p}{Q_p}s+\omega_p^2}=\frac{\frac{G_2+G_6}{G_2}s^2}{s^2+\frac{G_8}{C_7}s+\frac{G_1G_4G_6}{G_2C_3C_7}}$$

$$K=\frac{G_2+G_6}{G_2}=1+\frac{G_6}{G_2}=1+\frac{R_2}{R_6}$$

$$\omega_p=\sqrt{\frac{G_1G_4G_6}{G_2C_3C_7}}=\sqrt{\frac{R_2}{R_1R_4R_6C_3C_7}}$$

$$\frac{\omega_p}{Q_p}=\frac{G_8}{C_7}\Rightarrow Q_p=\frac{C_7}{G_8}\sqrt{\frac{G_1G_4G_6}{G_2C_3C_7}}=\frac{1}{G_8}\sqrt{\frac{G_1G_4G_6C_7}{G_2C_3}}=R_8\sqrt{\frac{R_2C_7}{R_1R_4R_6C_3}}$$

$$T(j\omega) = \frac{\frac{G_2}{C_7}\omega^2}{-\omega^2 + \frac{G_8}{C_7} j\omega + \frac{G_1 G_4 G_6}{G_2 C_3 C_7}}$$

$$|T(j\omega)| = \frac{|N(j\omega)|}{|D(j\omega)|} = \frac{\frac{G_2 + G_6\omega^2}{G_2}}{\sqrt{\left(\frac{G_1 G_4 G_6}{G_2 C_3 C_7} - \omega^2\right)^2 + \left(\frac{G_8}{C_7}\omega\right)^2}} \Rightarrow \alpha(\omega) = 20 \log |T(j\omega)| \quad [dB]$$

$$\varphi(\omega) = \operatorname{arctg} \frac{\operatorname{Im} N(j\omega)}{\operatorname{Re} N(j\omega)} - \operatorname{arctg} \frac{\operatorname{Im} D(j\omega)}{\operatorname{Re} D(j\omega)} = 0 - \operatorname{arctg} \frac{\frac{G_8}{C_7}\omega}{\frac{G_1 G_4 G_6}{G_2 C_3 C_7} - \omega^2}$$

1) Butterworth $n = 4$, $f_g = 5$ kHz

$$|H_n(j\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_g}\right)^{2n}}} \Rightarrow |H_4(j\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega}{2\pi \cdot 5 \cdot 10^3}\right)^8}} = \sqrt{\frac{1}{1 + \frac{\omega^8}{\pi^8 10^{24}}}}$$

$$\omega_{pk} = \sqrt{\sin^2\left(\frac{2k-1}{2n}\pi\right) + \cos^2\left(\frac{2k-1}{2n}\pi\right)} = 1 \quad \forall k$$

$$q_{pk} = \frac{1}{2 \sin\left(\frac{2k-1}{2n}\pi\right)} \qquad k = 1, 2$$

$$q_{p1} = \frac{1}{2 \sin \frac{\pi}{8}} = 1,30656, \qquad q_{p2} = \frac{1}{2 \sin \frac{3\pi}{8}} = 0,5412$$

$$H_4(s) = H_{21}(s) H_{22}(s) = \frac{K s^2}{s^2 + 1,3066 s + 1} \cdot \frac{K s^2}{s^2 + 0,5412 s + 1}$$

pretpostavka: $R_1 = R_2 = R_4 = R_6 = R_8 = R = 1$ kΩ

$C_{31} = ?$, $C_{71} = ?$

$$K_1 = 1 + \frac{R_2}{R_6} = 1 + \frac{R}{R} = 2$$

$$\frac{\omega_p}{Q_p} = \frac{G_8}{C_{71}} = 1,3066 \Rightarrow C_{71} = \frac{1}{1,3066 \cdot 10^3} = 765\ \mu F$$

$$\omega_p = \sqrt{\frac{R_2}{R_1 R_4 R_6 C_{31} C_{71}}} = \sqrt{\frac{R}{R^2 C_{31} C_{71}}} = 1 \Rightarrow C_{31} = \frac{1}{765 \cdot 10^{-6} \cdot 10^3} = 1,31\ mF$$

$$K_2 = 1 + \frac{R_2}{R_6} = 1 + \frac{R}{R} = 2$$

$$\frac{\omega_p}{Q_p} = \frac{1}{R_8 C_{72}} = 0{,}5412 \Rightarrow C_{72} = \frac{1}{0{,}5412 \cdot 10^3} = 1{,}85 \text{ mF}$$

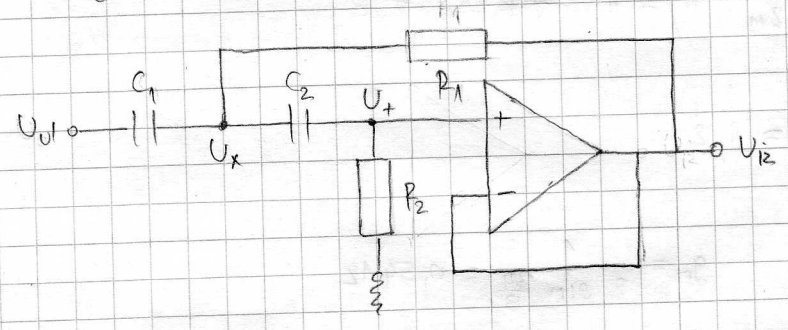
$$\omega_p = \sqrt{\frac{R_2}{R_1 R_4 R_6 C_{32} C_{72}}} = \sqrt{\frac{R}{R^2 C_{32} C_{72}}} = 1 \Rightarrow C_{32} = \frac{1}{1{,}85 \cdot 10^{-3} \cdot 10^3} = 541 \text{ } \mu\text{F}$$

)

$H_{VP}(s) = ?$, SAK sekcija

SALLEN-AND-KEY topologija je topologija elektroničkih filtara koja se koristi za izvedbu aktivnih filtara drugog reda, značajna je po svojoj jednostavnosti.

- realizacija VP Sallen-and-Key filtra izgleda ovako:



$$U_x\left(sC_1 + sC_2 + \frac{1}{R_1}\right) = U_{ul} sC_1 + U_+ sC_2 + \frac{U_{iz}}{R_1}$$

$$U_+\left(sC_2 + \frac{1}{R_2}\right) = U_x sC_2$$

$$U_+ = U_{iz}$$

$$U_x(sC_1 + sC_2 + G_1) = U_{ul} sC_1 + U_{iz}(sC_2 + G_1) \quad (1)$$

$$U_{iz}(sC_2 + G_2) = U_x sC_2 \quad (2)$$

$$U_x = \frac{sC_2 + G_2}{sC_2} U_{iz} \quad (2)$$

$$\frac{sC_2 + G_2}{sC_2} U_{iz}(sC_1 + sC_2 + G_1) = U_{ul} sC_1 + U_{iz}(sC_2 + G_1) \quad (2) \to (1)$$

$$\left[\frac{s C_2 + G_2}{s C_2}(s C_1 + s C_2 + G_1) - (s C_2 + G_1)\right]\frac{U_{iz}}{s C_1} = U_{ul}$$

$$\frac{s^2 C_1 C_2 + \cancel{s^2 C_2^2} + s G_1 C_2 + s G_2 C_1 + s G_2 C_2 + G_1 G_2 - \cancel{s^2 C_2^2} - s G_1 C_2}{s^2 C_1 C_2} = \frac{U_{ul}}{U_{iz}}$$

$$T_{vp}(s) = \frac{U_{iz}(s)}{U_{ul}(s)} = \frac{s^2 C_1 C_2}{s^2 C_1 C_2 + s G_2(C_1 + C_2) + G_1 G_2}$$

$$T_{vp}(s) = \frac{U_{iz}(s)}{U_{ul}(s)} = \frac{\frac{C_1 C_2}{C_1 C_2} s^2}{s^2 + \frac{G_2(C_1 + C_2)}{C_1 C_2} s + \frac{G_1 G_2}{C_1 C_2}}$$

$$T_{vp}(s) = \frac{s^2}{s^2 + \frac{G_2(C_1 + C_2)}{C_1 C_2} s + \frac{G_1 G_2}{C_1 C_2}} = \frac{s^2}{s^2 + \frac{\omega_p}{Q_p} s + \omega_p^2}$$

$K = 1$

$$\omega_p = \sqrt{\frac{G_1 G_2}{C_1 C_2}} = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}, \quad f_0 = \frac{\omega_p}{2\pi}$$

$$\frac{\omega_p}{Q_p} = \frac{G_2(C_1 + C_2)}{C_1 C_2} \Rightarrow Q_p = \frac{C_1 C_2}{G_2(C_1 + C_2)}\omega_p = \frac{R_2 C_1 C_2}{(C_1 + C_2)}\cdot\frac{1}{\sqrt{R_1 R_2 C_1 C_2}} = \frac{1}{C_1 + C_2}\sqrt{\frac{R_2 C_1 C_2}{R_1}}$$

- za $R_1 = R_2 = 10\ k\Omega$ i $C_1 = C_2 = 220\ pF$ dobije se VP SAK filte sa $f_0 = 72\ Hz$ i $Q_p = 0{,}5$

- sasvim općenito, jedan otpornik i jedan kondenzator odabiru ovisnosti od drugom, tako bi se smanjio stupanj slobode:

$R_1 = mR$, $R_2 = R$, $C_1 = nC$, $C_2 = C$, pa onda vrijedi:

$$\omega_p = \frac{1}{\sqrt{m n R^2 C^2}} = \frac{1}{RC\sqrt{mn}}$$

$$Q_p = \frac{1}{(m+1)C}\sqrt{\frac{RmC^2}{mR}} = \frac{1}{m+1}\sqrt{\frac{m}{n}}$$