

Simple Post-Filter neg. Feedback For Class-D Amplifiers Dsn Example

(Source : Charles Lehmann AES Paper Presentation 2009 in Denmark charles-lehmann@bluewin.ch)

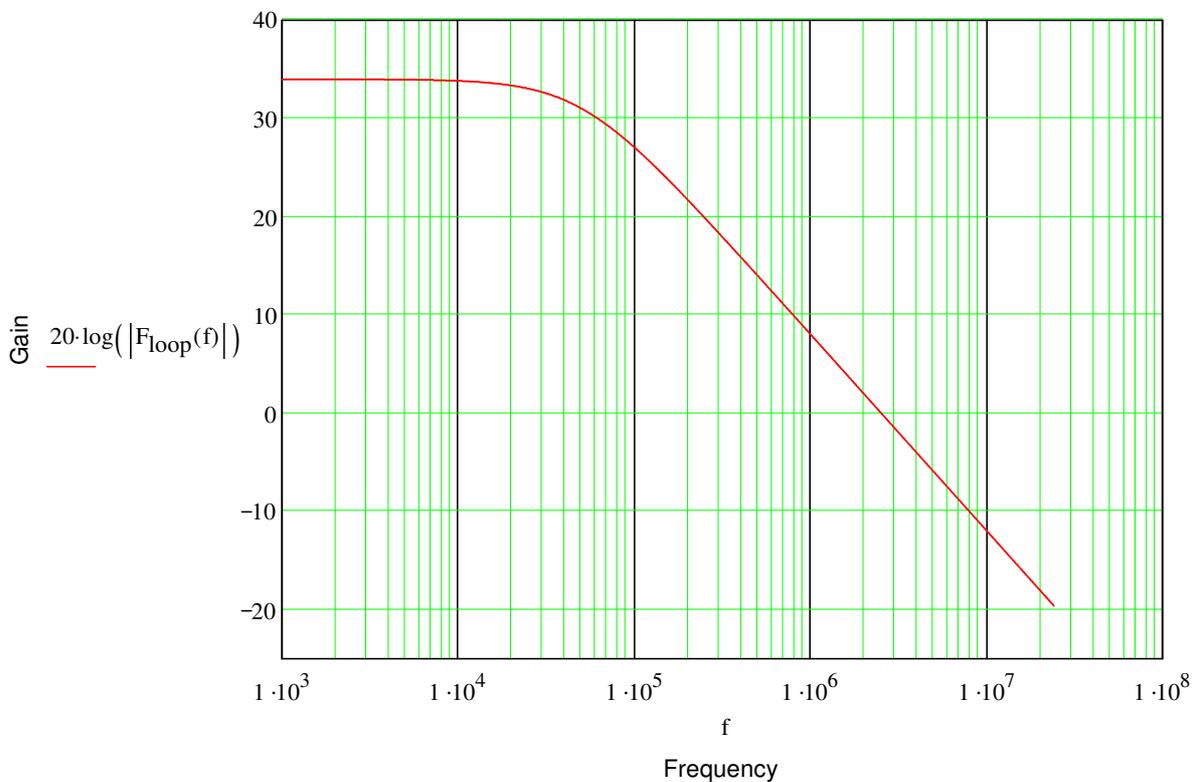
- Amplifier Specification Sheet **50Vrms (Carrier Based Amplifier)** Version using a Triangle Carrier Signal)

$$A_{\text{sw}} := 50 \quad (\text{DesiredClosedLoop})$$

$$f_L := (1.5 \cdot 10^4) \text{ Hz} \quad T_L := \frac{1}{2 \cdot \pi f_L} \quad T_L = 3.144 \times 10^{-6} \text{ s} \quad (\text{Desired 3dB Single Pole roll off of the whole amplifier})$$

$$F_{\text{loop}}(s) := A \cdot \frac{1}{1 + s \cdot T_L}$$

$$F_{\text{loop}}(f) := A \cdot \frac{1}{1 + j \cdot 2 \cdot \pi \cdot f \cdot T_L}$$



Desired single pole roll off of the switching amplifier. The figures below are a design example. All the variables can be changed to accommodate for another amplifier.

$$V_{\text{batt}} := \frac{170.0}{2} \text{ V} \quad V_{\text{Triangle}} := 3.0 \text{ V}$$

$$f_{\text{sw}} := 3.25 \cdot 10^5 \text{ Hz} \quad \text{Carrier Switching Frequency} \quad f_{\text{sw}} = 3.25 \times 10^5 \frac{1}{\text{s}}$$

$$R_i := 1 \text{ k}\Omega \quad \text{Amplifier Input Impedance}$$

Amplifiers LC-Outputfilter

$$F_{\text{filter}}(s) := \frac{1}{1 + s \cdot \frac{T_F}{Q_F} + s^2 \cdot T_F^2}$$

$R_{\text{Load}} := 50\Omega$

$L_{\text{Filt}} := 68\mu\text{H}$ $C_{\text{Filt}} := 600\text{nF}$

$Q_F := R_{\text{Load}} \cdot \sqrt{\frac{C_{\text{Filt}}}{L_{\text{Filt}}}}$ $Q_F = 4.697$

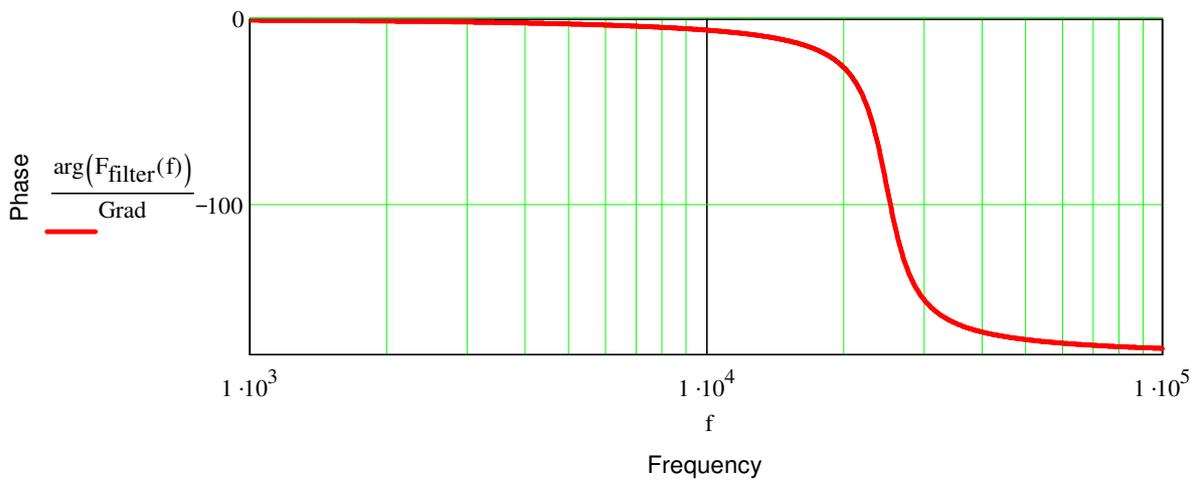
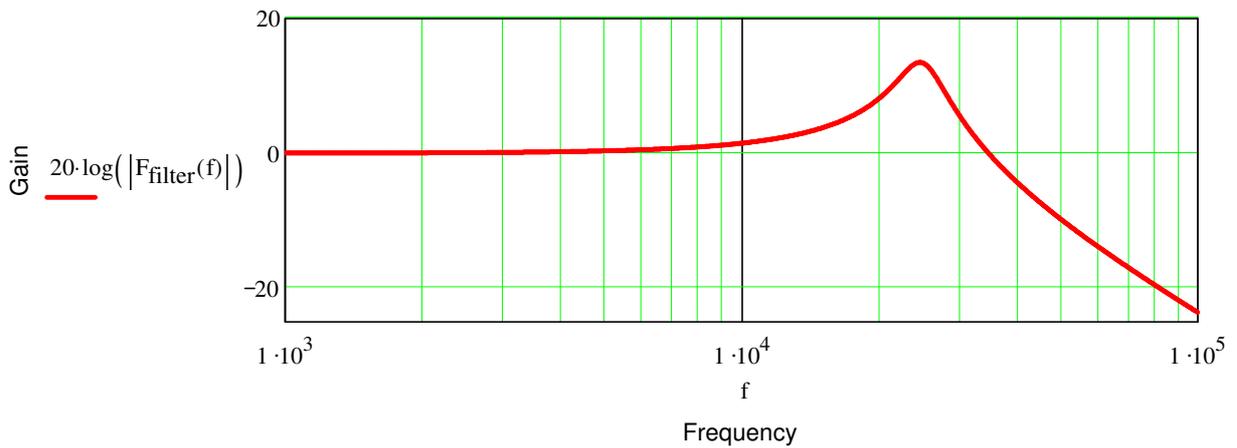
$T_F := \sqrt{L_{\text{Filt}} \cdot C_{\text{Filt}}}$

$T_F = 6.387 \times 10^{-6} \text{ s}$

$$F_{\text{filter}}(f) := \frac{1}{1 + j \cdot 2 \cdot \pi \cdot f \cdot \frac{T_F}{Q_F} - 4 \cdot \pi^2 \cdot f^2 \cdot T_F^2}$$

$F_{g_{\text{LC}}} := \frac{1}{2 \cdot \pi \cdot T_F}$

$F_{g_{\text{LC}}} = 2.492 \times 10^4 \frac{1}{\text{s}}$ (24 KHz)



IMO it is best calculate with a $Q > 0.5$. The filter peaks with the nominal load being used. Anyway it is just a startin point for component calculation. The amplifier must be able to tolerate any load $>$ nominal. Even no load!

Searching for the komplex Pole(s) Compensator Transfer Function

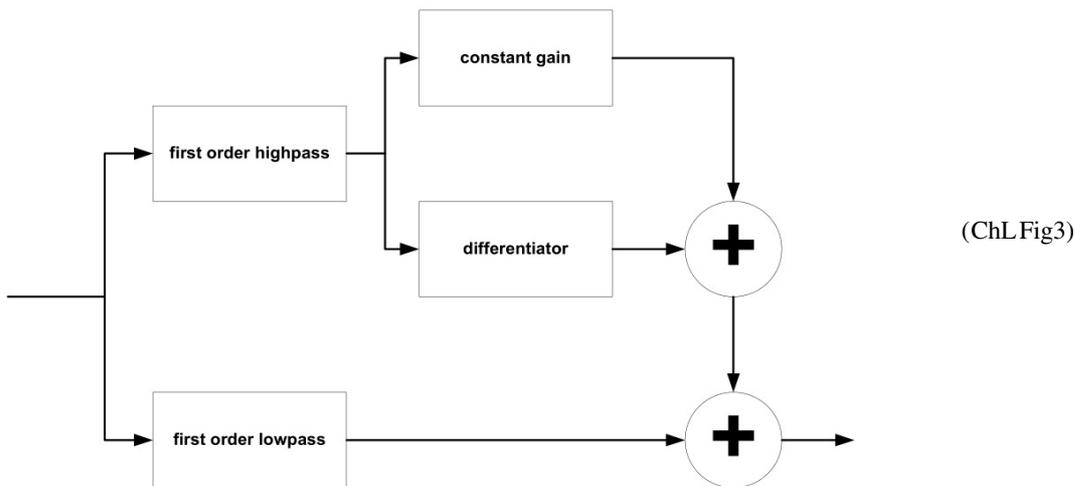
Searching for the Transfer function $f_x(s)$ that multiplied with the Transfer function of the LC-Output Filter $F_{filter}(s)$ results in the desired overall loop function $F_{loop}(s)$ (PT1 Behavior). See page 1 single pole role off.

$$F_{loop}(s) := A \cdot \frac{1}{1 + s \cdot T_L} = f_x(s) * F_{filter}(s) := \frac{1}{1 + s \cdot \frac{T_F}{Q_F} + s^2 \cdot T_F^2} \quad (\text{ChLEq4})$$

Rearranging the equation above results in the following :

$$f_x(s) := A \cdot \left[\frac{1}{1 + s \cdot T_L} + \frac{s \cdot T_L}{1 + s \cdot T_L} \cdot \left(\frac{T_F}{Q_F \cdot T_L} + s \cdot T_L \cdot \frac{T_F^2}{T_L^2} \right) \right] \quad (\text{ChLEq7})$$

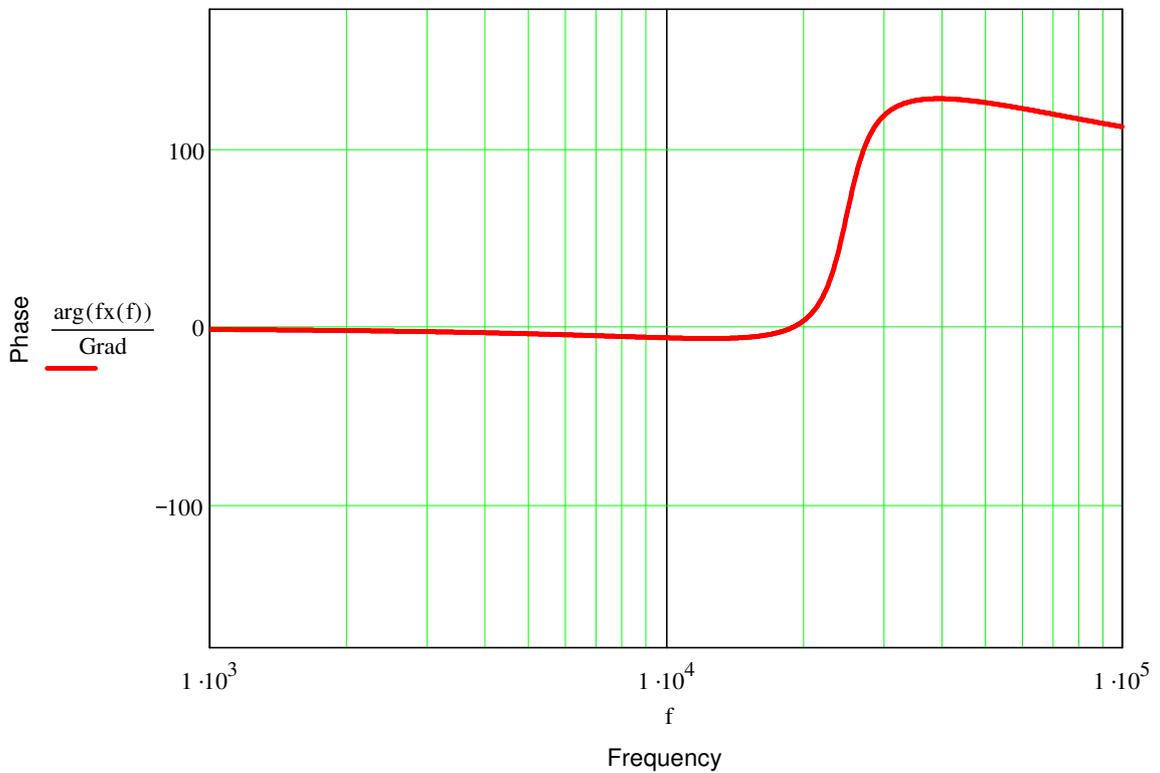
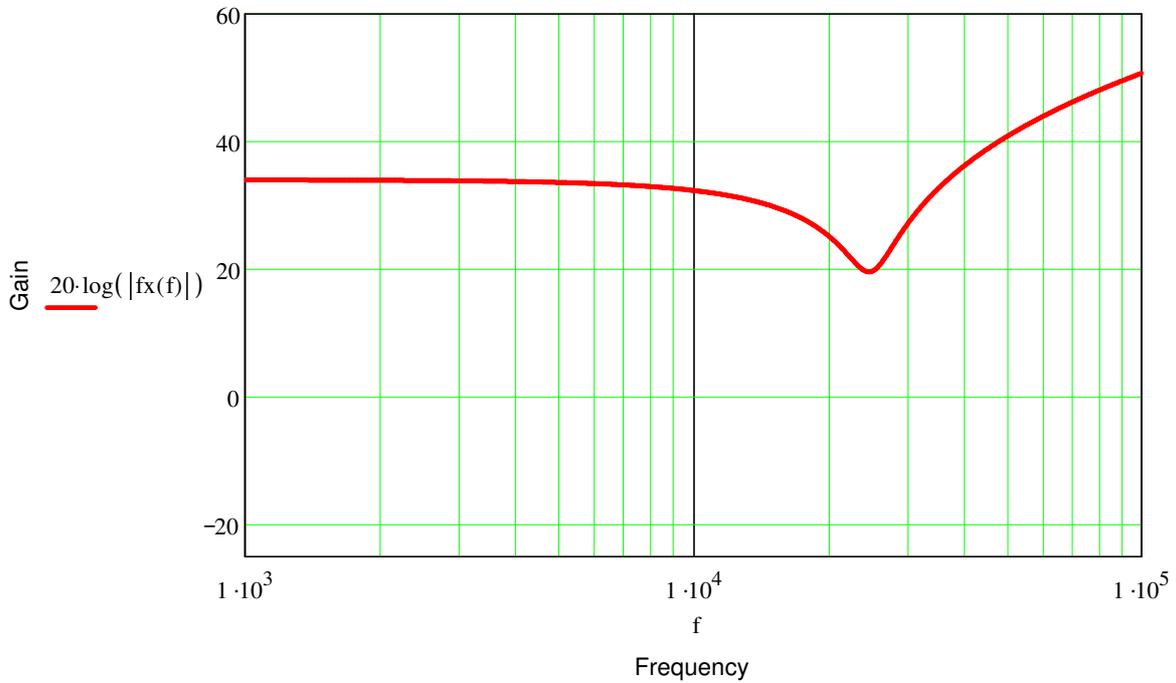
A possible solution for the linear system is the following topology for f_x



Complex Pole ($Q > 0.5$) Compensator Transfer Function

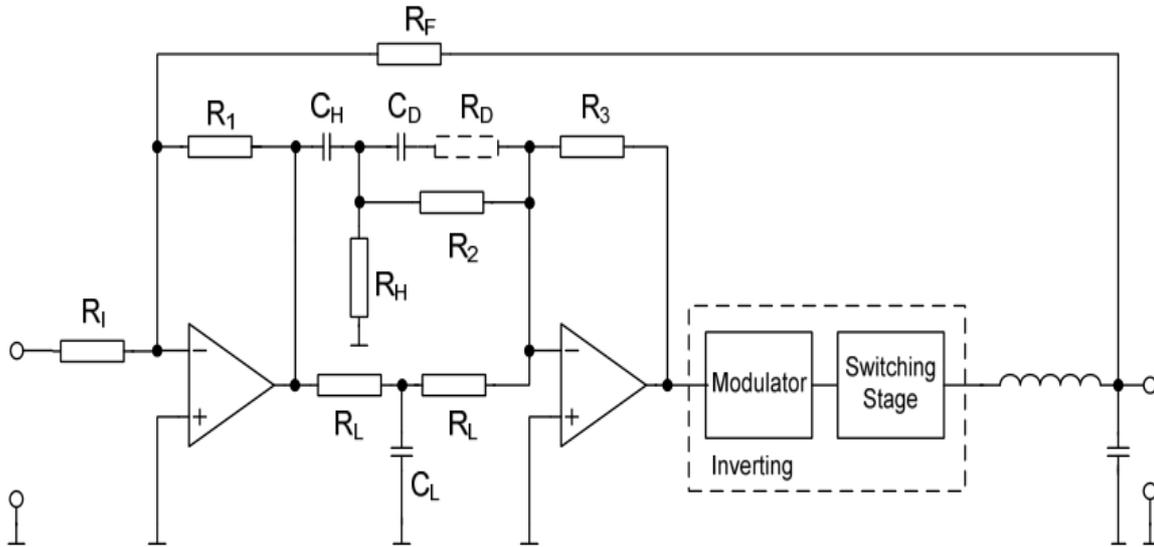
$$f_x(f) := A \cdot \left[\frac{1}{1 + j \cdot 2 \cdot \pi \cdot f \cdot T_L} + \frac{j \cdot 2 \pi \cdot f \cdot T_L}{1 + j \cdot 2 \cdot \pi \cdot f \cdot T_L} \cdot \left(\frac{T_F}{Q_F \cdot T_L} + j \cdot 2 \cdot \pi \cdot f \cdot T_L \cdot \frac{T_F^2}{T_L^2} \right) \right]$$

Amplitude & Phase Plot for the Complex Pole Compensator ($Q > 0.5$) $f_x(f)$



If this transfer function exists and can be mapped to real world circuits, then the initial phase margin of the whole amplifier will be close to 90 degrees.

For a Half Bridge like topology (ChL AES paper) the following mapping can be used to get this transfer function $f_x(f)$



- The closed loop gain A_{cl} in the topology above is : $A_{cl} := -\frac{R_f}{R_i}$ see Picture of Topology

- Modulator Gain is (inverting Power Comparator): $A_{HS} := \frac{V_{batt}}{V_{Triangle}}$ $A_{HS} = 28.333$

$$A_{loop} := \frac{-R_1 \cdot R_3}{R_F} \cdot \frac{1}{2R_L} \cdot \frac{1}{1 + s \cdot 0.5R_L \cdot C_L} + \frac{s \cdot C_H \cdot \left(\frac{R_H \cdot R_2}{R_2 + R_H} \right)}{1 + s \cdot C_H \cdot \left(\frac{R_H \cdot R_2}{R_2 + R_H} \right)} \cdot \left(\frac{1}{R_2} + s \cdot C_D \right) \cdot A_{HS} \cdot F_{filter}(s) \quad (ChLEq8)$$

Approximation : $A_{loop} := \frac{-R_1 \cdot R_3}{2 \cdot R_F \cdot R_L} \cdot \frac{1}{1 + s \cdot 0.5 \cdot R_L \cdot C_L} \cdot A_{HS}$

The forward transfer function is :

$$A_F := \frac{-R_1 \cdot R_3}{R_i} \cdot \frac{1}{2R_L} \cdot \frac{1}{1 + s \cdot 0.5R_L \cdot C_L} + \frac{s \cdot C_H \cdot \left(\frac{R_H \cdot R_2}{R_2 + R_H} \right)}{1 + s \cdot C_H \cdot \left(\frac{R_H \cdot R_2}{R_2 + R_H} \right)} \cdot \left(\frac{1}{R_2} + s \cdot C_D \right) \cdot A_{HS} \cdot F_{filter}(s) \quad (ChLEq9)$$

Approximation forward transfer function is :

$$A_{IF} := \frac{-R_1 \cdot R_3}{2 \cdot R_1 \cdot R_L} \cdot \frac{1}{1 + s \cdot 0.5 \cdot R_L \cdot C_L} \cdot A_{HS}$$

The closed loop gain : $A_{cl} := A$ (from Amplifier Spec Pg 1) $R_f := A_{cl} \cdot R_i$ $R_f = 5 \times 10^4 \Omega$

- Calculation of the Unity Gain Point. The amplifier is a "natural" sampling Amplifier. Sampling Theorem applies.

Specify nyquist distance : $D_{Nyquist} := 3.25$

$$\text{Unity gain point : } f_T := \frac{f_{sw}}{D_{Nyquist}} \quad f_T = 1 \times 10^5 \frac{1}{s}$$

(feedback factor)

The Feedback Factor is : $A_{loop} := \frac{f_T}{f_L}$ $A_{loop} = 1.975$

$$A_{fbf} := \text{rund}(A_{loop})$$

DC-Gain forward path is : $A_{cl} \cdot A_{fbf} = 100$

According to equation 9 (ChL eq. 9) the DC gain of the forward Function is : is :

$$A_{IF} := \frac{-R_1 \cdot R_3}{2 \cdot R_1 \cdot R_L} \cdot A_{HS}$$

$$\text{Select } R_L := 1k\Omega \quad \frac{A_{cl} \cdot A_{fbf}}{A_{HS}} = 3.529$$

$$\text{Minimum Compensator internal DC Gain : } \text{IntGain}_{Min} := \frac{A_{cl} \cdot A_{fbf} \cdot 2}{A_{HS}} \cdot R_1 \cdot R_L \quad \text{IntGain}_{Min} = 7.059 \times 10^6 \Omega^2$$

$$R_1 \text{ and } R_3 : \sqrt{\text{IntGain}_{Min}} = 2.657 \times 10^3 \Omega$$

$R_1 := 2.7k\Omega$ $R_3 := 2.7k\Omega$ Other gain settings are possible as long as the product is about the same.

$$C_L := \frac{1}{2 \cdot \pi \cdot f_L \cdot 0.5 \cdot R_L} \quad (\text{ChL Eq11}) \quad C_L = 6.288 \times 10^{-9} \text{ F} \quad (\text{select } 6.2 \text{ nF !})$$

$$R_2 := 2 \cdot R_L \cdot \frac{Q_F \cdot F_{gLC}}{f_L} \quad (\text{ChL Eq12}) \quad R_2 = 4.623 \times 10^3 \Omega \quad (\text{select } 4.7 \text{ kOhm!})$$

$R_H := 1.5k\Omega$ (R_H shall be reasonable smaller than R_2)

$$C_H := \frac{R_H + R_2}{2 \cdot \pi \cdot f_L \cdot R_H \cdot R_2} \quad (\text{ChLEq13}) \quad C_H = 2.776 \times 10^{-9} \text{ F} \quad (\text{select } 2.7 \text{ nF !})$$

$$C_D := \frac{1}{4 \cdot \pi \cdot f_L \cdot R_L} \cdot \left(\frac{f_L}{F_{gLC}} \right)^2 \quad (\text{ChLEq14}) \quad C_D = 6.489 \times 10^{-9} \text{ F} \quad (\text{select } 6.8 \text{ nF !})$$