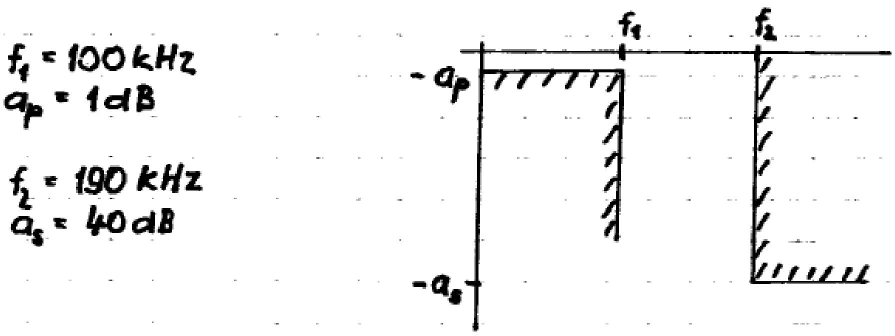
Návrh a realizace filtru typu DP pomocí simulace LC prototypu

Jií Hospodka

Návrh viz worksheety c:\Users\hospodka\Dropbox\vyuka\tes\filtry\.

Navrhnte filtr s Cauerovou aproximací modulové charakteristiky splující následující specifikaci a provedte syntézy LC filtru pro realizaci nalezené penosové funkce.
Návrh lze provést v internetové aplikaci knihovny Syntfil.




```
> restart;
> with(Syntfil);
> with(PraCAn);
> Digits:=20:
```

[*ARCBlock*, *ARCBlock1*, *ARCRoundR*, *ARCSynt*, *ARCSyntBP*, *ARCSyntBS*, *ARCSyntHP*, *ARCSyntLP*, *BP22NLP*, *BP2NLP*, *BS22NLP*, *BS2NLP*, *Bessel*, *BesselGenerator*, *BesselNLPOrder*, *BesselPoles*, *Bessel_asnew*, *BodePlot*, *Butterworth*, *ButterworthNLPOrder*, *ButterworthPoles*, *Butterworth_asnew*, *Cauer*, *CauerB*, *CauerBOmega*, *CauerBPolesZeros*, *CauerC*, *CauerCOmega*, *CauerCPolesZeros*, *CauerNLPOrder*, *CauerPolesZeros*, *Cauer_asnew*, *Chebyshev*, *ChebyshevC*, *ChebyshevCPoles*, *ChebyshevNLPOrder*, *ChebyshevPoles*, *Chebyshev_asnew*, *DroppNLP*, *ElemsBP*, *ElemsBP2*, *ElemsBP2m*, *ElemsBPm*, *ElemsBS*, *ElemsBS2*, *ElemsBS2m*, *ElemsBSm*, *ElemsHP*, *ElemsLP*, *GroupDelayH*, *HP2NLP*, *InvChebyshev*, *InvChebyshevB*, *InvChebyshevBPolesZeros*, *InvChebyshevPolesZeros*, *LP2NLP*, *LTC1060Synt*, *MagnitudeH*, *MagnitudeHdB*, *MakeARCFilter*, *MakeH*, *MakeLCLadder*, *MakeRealL*, *ModuleApply*, *NLP2BP*, *NLP2BP2*, *NLP2BS*, *NLP2BS2*, *NLP2HP*, *NLP2LP*, *PhaseH*, *SetOAModels*, *SetSyntfilDir*, *ShowOAModels*, *Syntfil2LaTeX*, *TestCharEqn*, *round2row*, *sortzeros*]

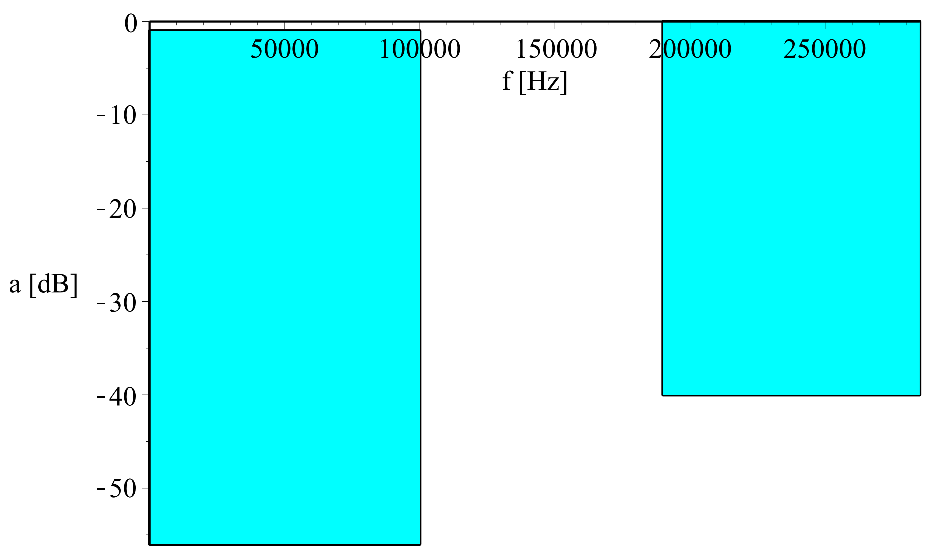
"Compiled 8 December 2015 - 23:43:58 in Maple 10.02, IBM INTEL NT, Nov 8 2005 Build ID 208934"

[*Analyze*, *ChangeElement*, *CreateTestcase*, *GetBranchVoltage*, *GetBranches*, *GetEqsVariables*, *GetEquations*, *GetExpandedModels*, *GetExpandedStructure*, *GetLastResults*, *GetLinPar*, *GetMatrix*, *GetNelinElems*, *GetNetlist*, *GetNodeVoltage*, *GetNodes*, *GetVariables*, *GetWinSpiceResults*, *ModuleApply*, *ParseCircuit*, *RunTestcase*, *RunWinSpice*, *SaveNetlist*, *SaveTestcase*, *SetAnalysis*, *SetOptions*, *TF2AC*, *WinSpice*] **(1)**

```
> fp:=100e3: fs:=190e3: ap:=1: as:=40:
```

Transformace toleranního schématu daného filtrtu dolní propusti (LP) na nornmovanou dolní propust (NLP).

```
> infolevel[syntfil]:=3:   #zajistí vykreslení toleranního
  schématu
> x:=LP2NLP(fp,fs,ap,as);
> infolevel[syntfil]:=1:
Filter specification:
fp = 100000.000000 Hz
fs = 190000.000000 Hz
ap = 1.000000 dB
as = 40.000000 dB
```




```
Specification of NLP:
Os = 1.900000 1/s
ap = 1.000000 dB
as = 40.000000 dB
```

$x := 1.9000000000000000000, 1, 40$ **(2)**

```
> Nc:=CauerNLPOrder(x);
> Cauer_asnew(Nc);
```

$Nc := 4, 1.9000000000000000000, 1$

49.823946299187844238 **(3)**

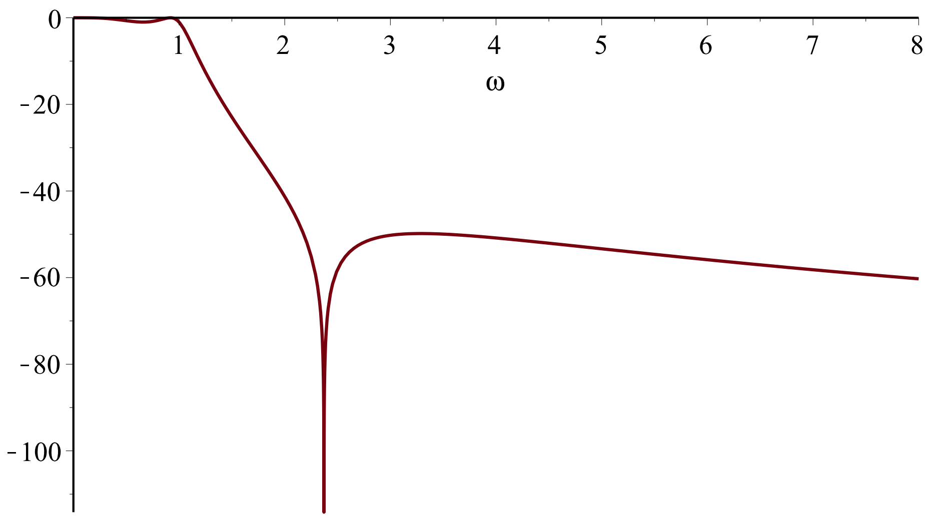
```
> #infolevel[syntfil]:=5:
> Gc,poles,zeros2:=CauerPolesZeros(Nc);
> g,chf,zer:=CauerC(Nc,p);
> infolevel[syntfil]:=1:
```

Gc, *poles*, *zeros2* := 309.88268833487895101, [-0.35302736109810593230

$+ 0.44708660013879864499\,I,\ -0.35302736109810593230$
$- 0.44708660013879864499\,I,\ -0.11929556054436121978$
$+ 0.98982441675609000756\,I,\ -0.11929556054436121978$
$- 0.98982441675609000756\,I],\ [2.0335752720999972443\,I,$
$-2.0335752720999972443\,I,\ 4.6413602404101304012\,I,\ -4.6413602404101304012\,I]$

$$g, chf, zer := \frac{1}{p^2 + 5.6252303234148591789}\big(14.910688506878234275\,p^4 + 19.193470027605093109\,p^3 + 24.910348496010359208\,p^2 + 16.401293693070333209\,p + 5.6252303234148591787\big),\ \frac{\left(14.910688506878234275\,p^2 + 12.557153285385487265\right)p^2}{p^2 + 5.6252303234148591789},\ \left[\begin{array}{cc} 2.3717568010685368706\,I & -2.3717568010685368706\,I \end{array}\right] \quad \mathbf{(4)}$$

```
> plot(MagnitudeHdB(1/g)(omega),omega=0..8);
```




```
> R1_NLP:=1:
> infolevel[syntfil]:=2:
> elems_NLP:=DroppNLP('common',R1_NLP,rear,T,g,chf,zer):
```

$$Rem\_matrix = \left[\begin{array}{cc} 0.99999999971715728598 & 0. \\ 0. & 1.0000000002828427160 \end{array}\right]$$

$$type = LC\_NLP\_common$$

$$R1 = 1.$$

$$R2 = 1.0000$$

$$block\,(1),\ [elements = \{L1 = 1.5537\},\ Z = p\,L1,\ orientation = direct]$$

$$block\,(2),\ \left[elements = \{C1 = 1.4819\},\ Z = \frac{1}{p\,C1},\ orientation = shunt\right]$$

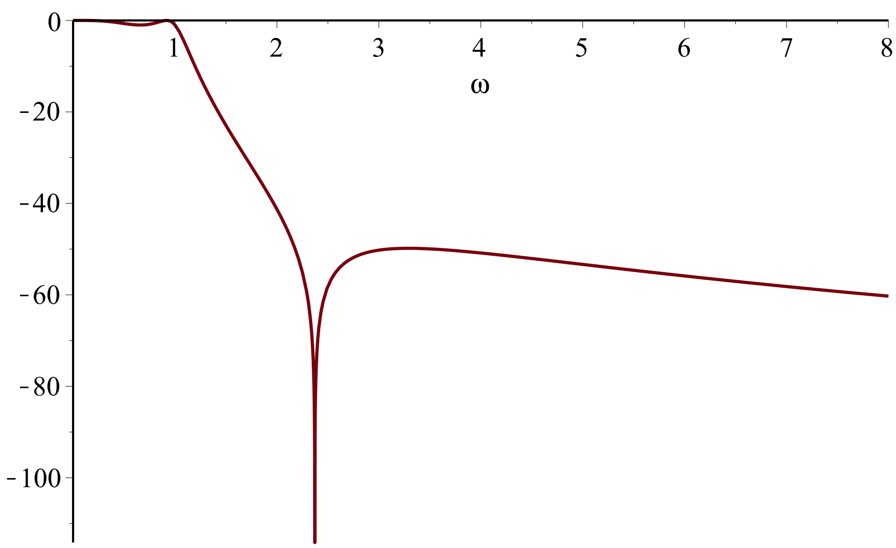
$$block(3), \left[elements = \{C1 = 0.13053, L1 = 1.3619\}, Z = \frac{1}{\frac{1}{p\,L1} + p\,C1}, orientation = direct\right]$$

$$block(4), \left[elements = \{C1 = 1.4338\}, Z = \frac{1}{p\,C1}, orientation = shunt\right] \quad \textbf{(5)}$$

```
> H_NLP:=MakeH(elems_NLP);
```

$$H\_NLP := (0.99999999999999999999\,p^2 + 5.6252303234148591792) / (14.910688511095652682\,p^4 + 19.193470027605117911\,p^3 + 24.910348499562091655\,p^2 + 16.401293693070344576\,p + 5.6252303234148591792) \quad \textbf{(6)}$$

```
> plot(MagnitudeHdB(H_NLP)(omega),omega=0..8);
> evalf(MagnitudeHdB(H_NLP)(1));
```



$$-0.99999999906085467803 \quad \textbf{(7)}$$

```
> R_LP:=1:
> infolevel[syntfil]:2:
> elems_LP:=ElemsLP(elems_NLP,R_LP,fp):
```

$$type = LC\_LP\_common$$

$$R1 = 1$$

$$R2 = 1.0000000005656854248$$

$$block(1), [elements = \{L1 = 0.0000024728\}, Z = p\,L1, orientation = direct]$$

$$block(2), \left[elements = \{C1 = 0.0000023585\}, Z = \frac{1}{p\,C1}, orientation = shunt\right]$$

$$block(3), \left[elements = \{C1 = 2.0774\ 10^{-7}, L1 = 0.0000021676\}, Z = \frac{1}{\frac{1}{p\,L1} + p\,C1}, orientation = direct\right]$$

$$block(4),\ \left[elements = \{C1 = 0.0000022819\},\ Z = \frac{1}{p\,C1},\ orientation = shunt\right] \quad \textbf{(8)}$$

```
> Q:=50:
> elems_LPQ:=MakeRealL(elems_LP,Q,fp):
```

$$type = LC\_LP\_common\_Q$$

$$R1 = 1$$

$$R2 = 1.0000000005656854248$$

$$block(1),\ [elements = \{L1 = 0.0000024728,\ Rs1 = 0.031075\},\ Z = Rs1 + p\,L1,\ orientation = direct]$$

$$block(2),\ \left[elements = \{C1 = 0.0000023585\},\ Z = \frac{1}{p\,C1},\ orientation = shunt\right]$$

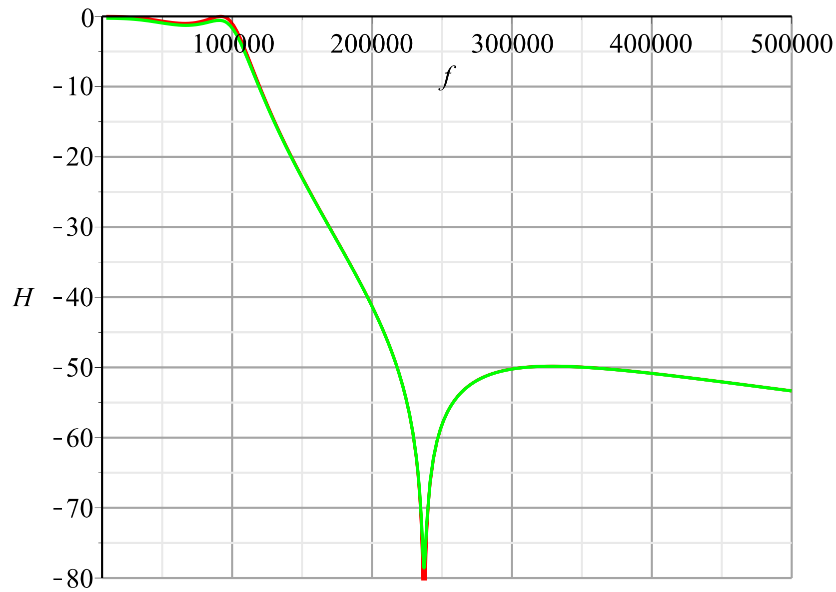
$$block(3),\ \left[elements = \{C1 = 2.0774\ 10^{-7},\ L1 = 0.0000021676,\ Rs1 = 0.027239\},\ Z = \frac{1}{\frac{1}{Rs1 + p\,L1} + p\,C1},\ orientation = direct\right]$$

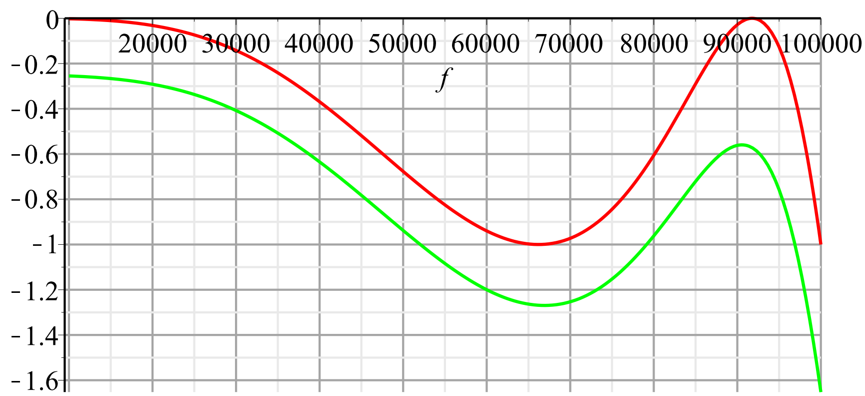
$$block(4),\ \left[elements = \{C1 = 0.0000022819\},\ Z = \frac{1}{p\,C1},\ orientation = shunt\right] \quad \textbf{(9)}$$

```
> H_LP:=MakeH(elems_LP);
> H_LPQ:=MakeH(elems_LPQ);
> mg_LP:=MagnitudeHdB(H_LP)(2*Pi*f): mg_LPQ:=MagnitudeHdB(H_LPQ)(2*Pi*f):
> plot([mg_LP,mg_LPQ],f=10e3..500e3,H=-80..0,color=[red,green],gridlines);
> plot([mg_LP,mg_LPQ],f=10e3..100e3,color=[red,green],gridlines);
> evalf(MagnitudeHdB(H_LP)(100e3*2*Pi));
```

$$H\_LP := (0.99999999999999999999\,p^2 + 2.2207519182846644126\ 10^{12}) \big/ (3.7769215221660464617\ 10^{-11}\,p^4 + 0.00003054735629979491340\,2p^3 + 24.910348499562091654\,p^2 + 1.0305236755103680731\ 10^{7}\,p + 2.2207519182846644128\ 10^{12})$$

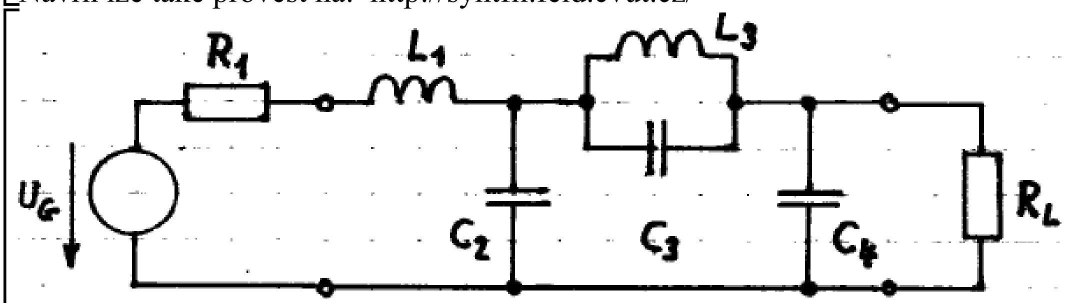
$$H\_LPQ := (1.0000000000000000000\,p^2 + 12566.370614359172954\,p + 2.2207519182846644127\ 10^{12}) \big/ (3.7769215221660464618\ 10^{-11}\,p^4 + 0.000031496600212372675882\,p^3 + 25.492116875848971032\,p^2 + 1.0620681349060130918\ 10^{7}\,p + 2.2855016304696529203\ 10^{12})$$





$$-0.99999999906085467795 \tag{10}$$

Návrh lze také provést na: http://syntfil.feld.cvut.cz/



Nornované prvky:

```
> ele_NLP:={L1=subs(eval(elems_NLP[1][elements]),L1),
> C2=subs(eval(elems_NLP[2][elements]),C1),
> L3=subs(eval(elems_NLP[3][elements]),L1),
> C3=subs(eval(elems_NLP[3][elements]),C1),
> C4=subs(eval(elems_NLP[4][elements]),C1),
  R1=eval(elems_NLP)[R1], R2=eval(elems_NLP)[R2]};
```

$$ele\_NLP := \{C2 = 1.4819020449663622408, C3 = 0.13052731125238878156, C4 = 1.4337641128303149295, L1 = 1.5537251465073974263, L3 = 1.3619410145879828687, R1 = 1, R2 = 1.0000000005656854248\} \quad \textbf{(11)}$$

Odnormování lze provést run ....

```
> omega_p:=evalf(2*Pi*fp);
> L1_NLP/omega_p;
```

$$omega\_p := 6.2831853071795864770\ 10^5$$

$$0.0000015915494309189533577\ L1\_NLP \quad \textbf{(12)}$$

... nebo lépe použít odnormované hodnoty pímo Syntfilem:

```
> ele_LP:={L1=subs(eval(elems_LP[1][elements]),L1),
> C2=subs(eval(elems_LP[2][elements]),C1),
> L3=subs(eval(elems_LP[3][elements]),L1),
> C3=subs(eval(elems_LP[3][elements]),C1),
> C4=subs(eval(elems_LP[4][elements]),C1),
  R1=eval(elems_LP)[R1], R2=eval(elems_LP)[R2]};
```

$$ele\_LP := \{C2 = 0.0000023585203563438470534, C3 = 2.0774066794312046237\ 10^{-7}, C4 = 0.0000022819064578471057583, L1 = 0.0000024728303727283158049, L3 = 0.0000021675964467126860878, R1 = 1, R2 = 1.0000000005656854248\} \quad \textbf{(13)}$$

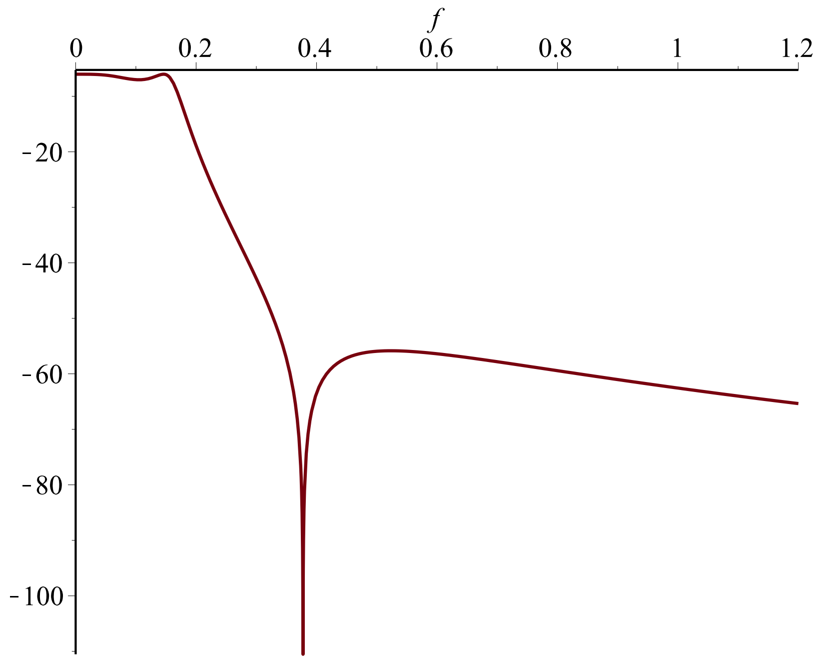
Pokud nevíme analýza ze Syntfilu, lze LC strukturu analyzovat pomocí PraCAnu:

```
> sch_LC:="netlist LC struktury
  V1 in 0 ac 1
  R1 in 1 1
  L1 1 2
  C2 2 0
  L3 2 out
  C3 2 out
  C4 out 0
  R2 out 0
  .end":
> ana_NLP:=PraCAn(sch_LC,ac):
> H_NLP_Pra:=subs(ele_NLP,subs(ana_NLP,v("out")));
```

$$H\_NLP\_Pra := \left(1.0000000005656854248\left(-7.0180979861446132126 f^2 + 1.\right)\right) \Big/ \left(-1692.7108988149458176\, \mathrm{I} f^3 + 36.639341557707213150\, \mathrm{I} f + 2.0000000005656854248 - 349.64653337676937951 f^2 + 8262.4122047955617858 f^4\right) \quad \textbf{(14)}$$

Pozor, napový penos - nutné násobit 2 (piíst 6dB)!

```
> plot(20*log10(abs(H_NLP_Pra)),f=0..1.2);
> evalf(20*log10(abs(subs(f=1/2/Pi,H_NLP_Pra))))+6;
```



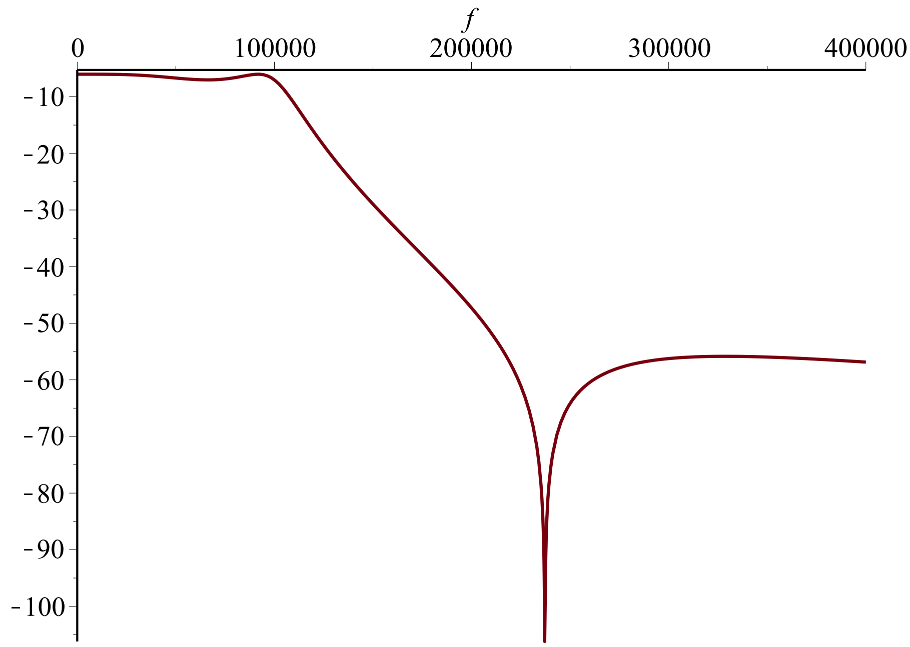
$$-1.0205999098837379960 \qquad \textbf{(15)}$$

```
> H_LP_Pra:=subs(ele_LP,subs(ana_NLP,v("out")));
```

$$H\_LP\_Pra := \left(1.0000000005656854248 \left(-1.7777049871851980999\ 10^{-11} f^2 + 1.\right)\right) \Big/ \left(-6.8240654798227851804\ 10^{-15}\, \mathrm{I} f^3 + 0.00005831332320541407314\,3\, \mathrm{I} f + 2.0000000005656854248 - 8.8566501545436083233\ 10^{-10} f^2 + 5.3013610672074069004\ 10^{-20} f^4\right) \qquad \textbf{(16)}$$

Pozor, napový penos - nutné násobit 2 (piíst 6dB)!

```
> plot(20*log10(abs(H_LP_Pra)),f=0..400e3);
> evalf(20*log10(abs(subs(f=100e3,H_LP_Pra))))+6;
```

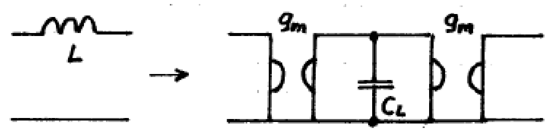


$$-1.0205999098837379974 \tag{17}$$

Návrh zapojení pro simulaci prvk s gyrátory

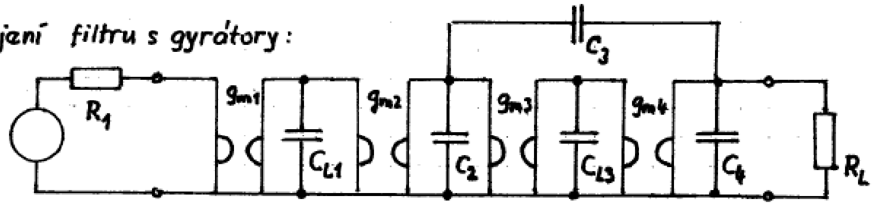
Pozor, neodpovídají hodnoty normovaných souástek (ze Syntfilu vyjdou mírn jinak).

Princip :



$$L_{ekv} = \frac{C_L}{g_m^2}$$

Zapojení filtru s gyrátory :



Volba g_m : podmínka : C_{L1} , C_{L3} přibližně shodné s C_2, C_4

vyhoví $g_{m1} = g_{m2} = g_{m3} = g_{m4} = g_m = 1$

hodnoty normovaných prvků : $C_L = L \cdot g_m^2$

$R_1 = 1$ $R_L = 1$ $g_m = 1$

$C_{L1} = 1{,}546$ $C_2 = 1{,}447$ $C_{L3} = 1{,}269$ $C_3 = 0{,}203634$ $C_4 = 1{,}368$

Frekvenční a impedanční odnormování :

$$C_{skut} = \frac{C_N}{\omega_N R_N} \qquad g_{m\,skut} = \frac{g_m}{R_N}$$

↓

tento vztah použiji pro určení R_N, chci-li skutečné hodnoty kapacit kondenzátorů mít v daném rozsahu.

Pro mikroelektronickou realizaci $C_{skut} \in \langle 1pF ; 50pF \rangle$

Volím $C_{skut\,min} = 2pF$ —> nejmenší normovaná kapacita je C_3 !

$$R_N = \frac{C_N}{\omega_N C_{skut}} \;\longrightarrow\; R_N = \frac{0{,}203634}{2\pi \cdot 10^5 \cdot 2 \cdot 10^{-12}} = 162\,046{,}8\,\Omega$$

Odnormované prvky : $R_1 = R_L = R_N$; $g_m = \frac{1}{R_N} = 6{,}171\,\mu S$ ($\mu A/V$)

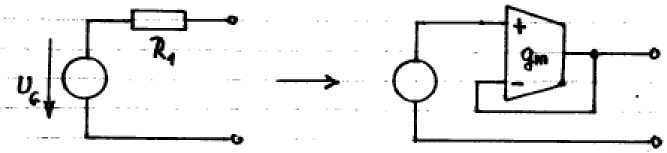
$C_{L1} = 15{,}18pF$; $C_2 = 14{,}21pF$; $C_{L3} = 12{,}46pF$; $C_3 = 2pF$; $C_4 = 13{,}44pF$

{*C3g* = 1.2819676618769963733 10^{-12}, *CI1* = 1.5259836230106436832 10^{-11}, *CI2* = 1.4554429118997880167 10^{-11}, *CI3* = 1.3376237672663985848 10^{-11}, *CI4*

= 1.40816447513744489634 10^{-11}}
Zde jsou hodnoty mírn posunuty (ze Syntfilu již takto vyšly normované hodnoty.

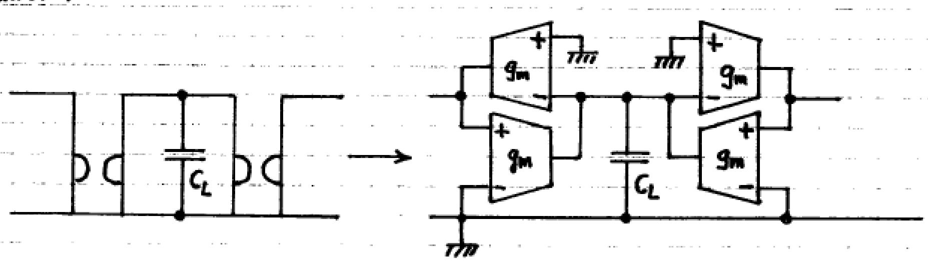
Zapojení OTA - C :

1) Vstupní část :

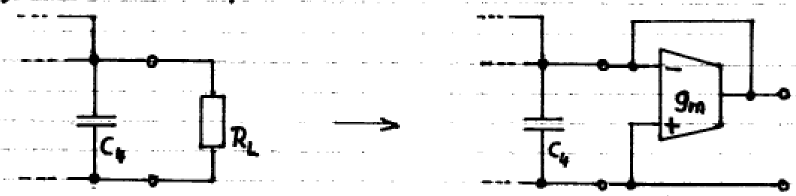


$g_m = \frac{1}{R_N}$

2) Induktor :

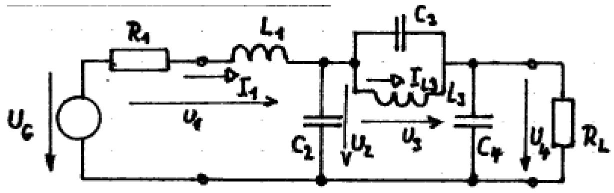


3) Zakončovací odpor :



$g_m = \frac{1}{R_L}$

Návrh funkní simulací



Obvodové rovnice:

$$I_1 = \frac{1}{R_1+pL_1}(U_G-U_2) \longrightarrow RI_1 = \frac{R}{R_1+pL_1}(U_G-U_2) \longrightarrow v_1 = \frac{R}{R_1+pL_1}(U_G-U_2)$$

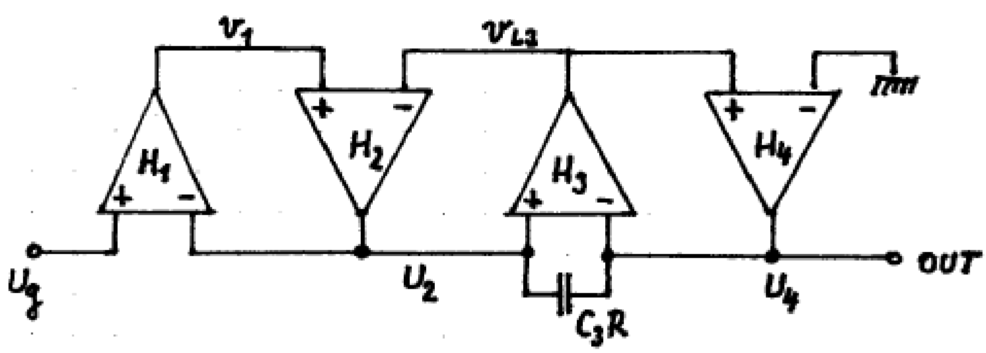
$$U_2 = \frac{1}{pC_2}\left(I_1 - I_{L3} - pC_3(U_2-U_4)\right) \longrightarrow U_2 = \frac{1}{pC_2R}\left(v_1 - v_{L3} - pC_3R(U_2-U_4)\right)$$

$$I_{L3} = \frac{1}{pL_3}(U_2-U_4) \longrightarrow v_{L3} = \frac{R}{pL_3}(U_2-U_4)$$

$$U_4 = \frac{1}{pC_4+1/R_L}\left(I_{L3}+pC_3(U_2-U_4)\right) \longrightarrow U_4 = \frac{1}{pC_4R+R/R_L}\left(v_{L3}+pC_3R(U_2-U_4)\right)$$

R je volitelný parametr (fiktivní rezistor).

Realizační struktura :




```
> H1:=R/(R1+s*L1);
> H2:=1/(s*C2*R);
> H3:=R/(s*L3);
> H4:=1/(R/RL+s*C4*R);
```

$$H1 := \frac{R}{R1 + L1\, s}$$

$$H2 := \frac{1}{s\, C2\, R}$$

$$H3 := \frac{R}{L3\, s}$$

$$H4 := \frac{1}{\frac{R}{RL} + s\, C4\, R} \quad \textbf{(2.1)}$$

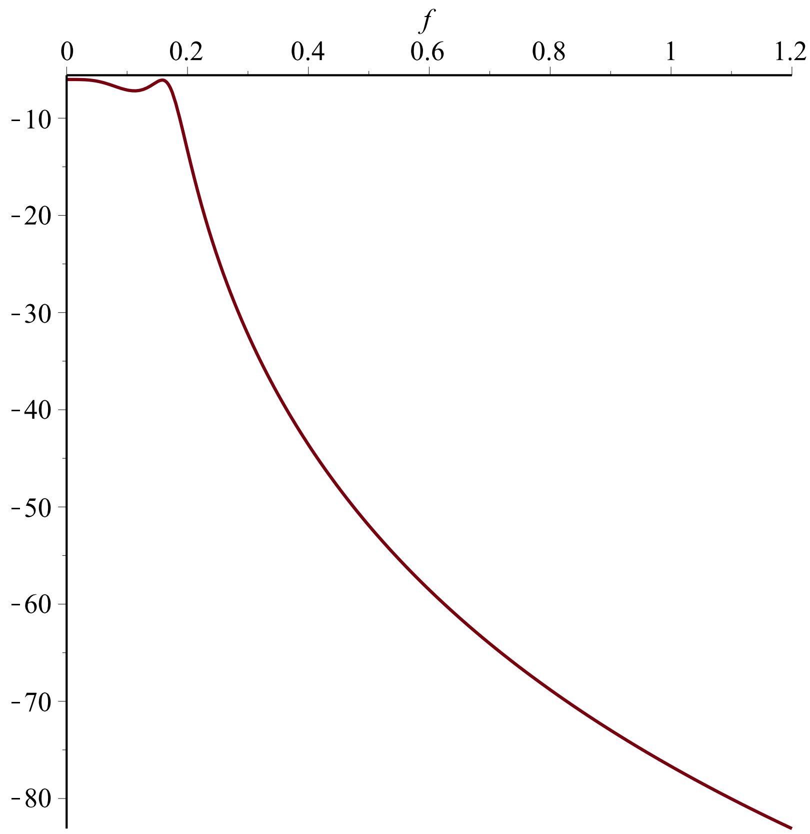
Analýza systémové struktury

Takto to nemže vyjít, protože C3 nemá vliv (je zapojen na výstupy napových zdroj)

```
> sch_sys:="netlist systémové struktury
  V1 in 0 ac 1
  E1 1 0 in 2 H1
  E2 2 0 1 3 H2
  E3 3 0 2 out H3
  C3 2 out C3*R
  E4 out 0 3 0 H4
  .end":
> ana_NLP_sys:=PraCAn(sch_sys,tf):
> H_NLP_sys_Pra:=subs({ele_NLP[],R1=R1_NLP,RL=R1_NLP,s=evalf(I*
  2*Pi*f)},subs(ana_NLP_sys,v("out")));
```

$$H\_NLP\_sys\_Pra := 1 \Big/ \left(2 + 36.639341547344042412\,\mathrm{I}\,f - 335.61033725573283191\,f^2 - 1495.6285740132807657\,\mathrm{I}\,f^3 + 7007.2751346175619903\,f^4\right) \quad \textbf{(2.1.1)}$$

```
> plot(20*log10(abs(H_NLP_sys_Pra)),f=0..1.2);
```



.... zkusit pedlat na proudové zdroje zatížené R, nepjde takto - PEDLAT!!!

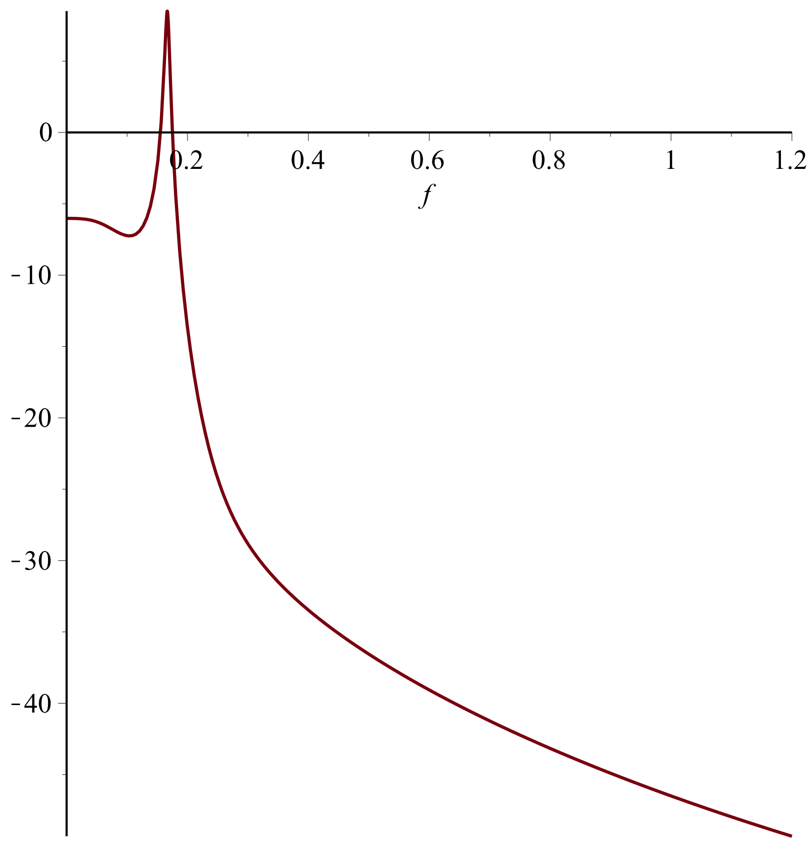
```
> sch_sys:="netlist systémové struktury
  V1 in 0 ac 1
  E1 1 0 in 2 H1
```

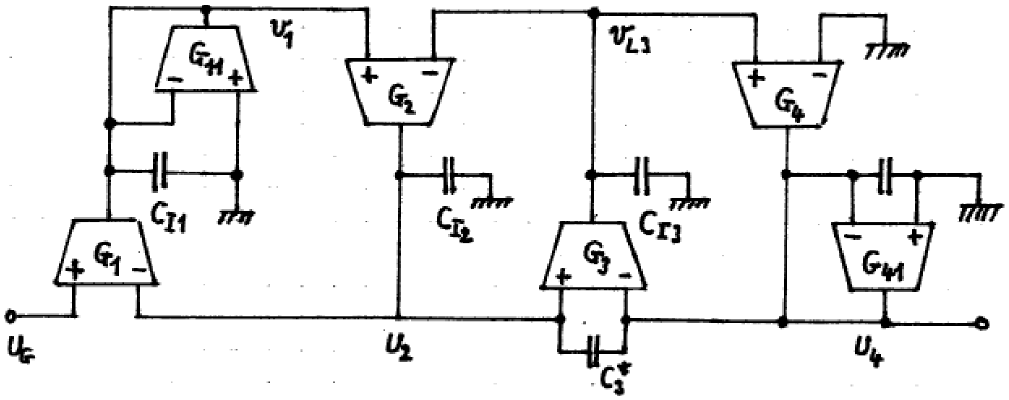
```
E2 2p 0 1 3 H2
Rp2 2p 2 R
E3 3 0 2 out H3
C3 2 out C3*R
E4 outp 0 3 0 H4
Rp4 outp out R
.end":
```

```
> ana_NLP_sys:=PraCAn(sch_sys,tf):
> H_NLP_sys_Pra:=subs({ele_NLP[],R1=R1_NLP,RL=R1_NLP,R=R1_NLP,
  s=evalf(I*2*Pi*f)},subs(ana_NLP_sys,v("out")));
```

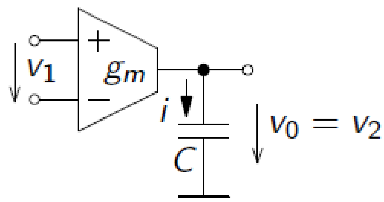
$$H\_NLP\_sys\_Pra := \left(1 - 7.0180979861446132126\, f^2 - 63.223276873348048917\, \mathrm{I} f^3\right) \Big/ \left(9460.4867359120129982\, f^4 + 11493.715052246182655\, \mathrm{I} f^5 - 1689.5437861215529509\, \mathrm{I} f^3 - 342.62843524187744512\, f^2 + 36.639341547344042412\, \mathrm{I} f + 2\right) \quad \textbf{(2.1.2)}$$

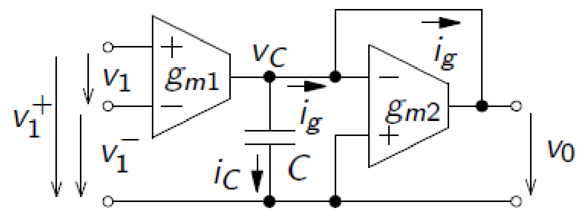
```
> plot(20*log10(abs(H_NLP_sys_Pra)),f=0..1.2);
```





Penos ideálního a ztrátového integrátoru:





$$H(s) = \frac{v_2}{v_1} = \frac{g_m}{sC}$$

$$v_0 = \frac{g_{m1}}{sC + g_{m2}}\left(v_1^{+} - v_1^{-}\right)$$

Pokud volíme $R = RL = R1$, budou všechny transkonduktance stejné a pak lze psát: gm1=gm11= gm2=......=gm41 a penosy jednotlivých OTA integrátor budou:

```
> H1g:=gm/(s*CI1+gm);
> H2g:=gm/(s*CI2);
> H3g:=gm/(s*CI3);
> H4g:=gm/(s*CI4+gm);
```

$$H1g := \frac{gm}{s\,CI1 + gm}$$

$$H2g := \frac{gm}{s\,CI2}$$

$$H3g := \frac{gm}{s\,CI3}$$

$$H4g := \frac{gm}{s\,CI4 + gm} \qquad \textbf{(2.2)}$$

```
> CI:=solve(subs({R=R1,RL=R1},{H1=H1g,H2=H2g,H3=H3g,H4=H4g}),
  {CI1,CI2,CI3,CI4});
```

$$CI := \left\{CI1 = \frac{gm\,L1}{R1},\ CI2 = gm\,R1\,C2,\ CI3 = \frac{gm\,L3}{R1},\ CI4 = gm\,C4\,R1\right\} \qquad \textbf{(2.3)}$$

C3g=C3*gm*R.

```
> CI_all:={C3g=C3*gm} union CI;
```

$$CI\_all := \left\{C3g = C3\ gm,\ CI1 = \frac{gm\ L1}{R1},\ CI2 = gm\ R1\ C2,\ CI3 = \frac{gm\ L3}{R1},\ CI4 = gm\ C4\ R1\right\} \quad \textbf{(2.4)}$$

Numericé hodnoty C a gm=6.171e-6.

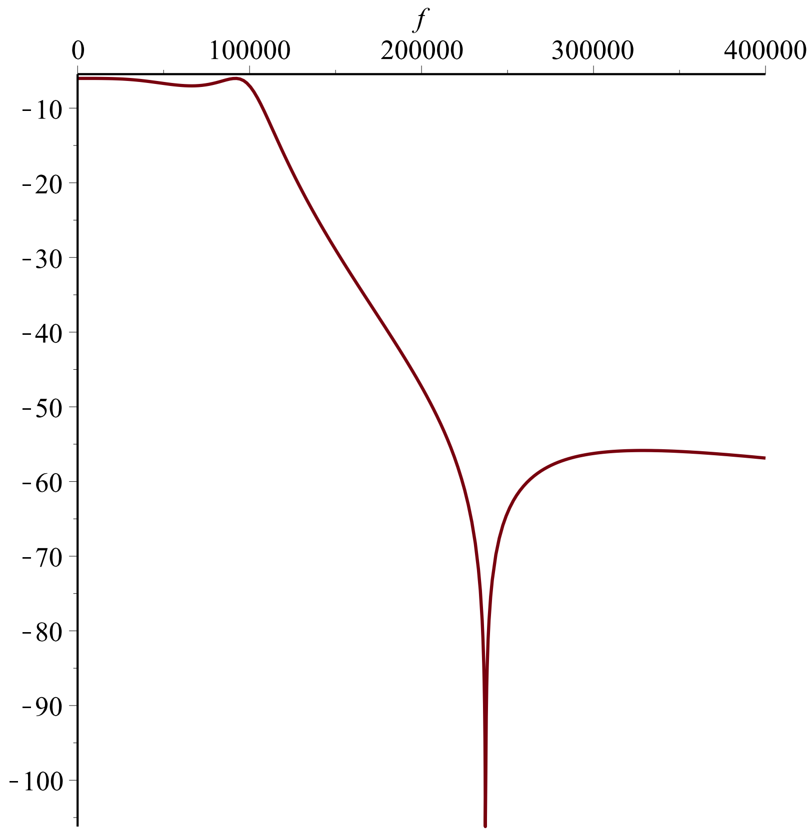
```
> CI_all_n:=subs({gm=6.171e-6} union ele_LP,CI_all);
```

$$CI\_all\_n := \{C3g = 1.2819676618769963733\ 10^{-12},\ CI1 = 1.5259836230106436832\ 10^{-11},\ CI2 = 1.4554429118997880167\ 10^{-11},\ CI3 = 1.3376237672663985848\ 10^{-11},\ CI4 = 1.4081644751374489634\ 10^{-11}\} \quad \textbf{(2.5)}$$

```
> sch_OTA:="netlist OTA struktury
  V1 in 0 ac 1
  G1 1 0 in 2 gm
  CI1 1 0
  G11 1 0 0 1 gm
  G2 2 0 1 3 gm
  CI2 2 0
  G3 3 0 2 out gm
  CI3 3 0
  C3 2 out C3g
  G4 out 0 3 0 gm
  CI4 out 0
  G14 out 0 0 out gm
  .end":
> ana_LP_OTA:=PraCAn(sch_OTA,ac):
> H_LP_OTA_Pra:=subs({gm=6.171e-6} union CI_all_n,subs
  (ana_LP_OTA,v("out")));
```

$$H\_LP\_OTA\_Pra := \left(3.8081241\ 10^{-11}\left(3.8081241\ 10^{-11} - 6.7697212043901440476\ 10^{-22} f^2\right)\right) \Big/ \left(9.8961295262572973120\ 10^{-36}\, \mathrm{I} f^3 - 8.4564868442948935698\ 10^{-26}\, \mathrm{I} f + 2.900361832200162\ 10^{-21} - 1.2843745029229962417\ 10^{-30} f^2 + 7.6879326446711889733\ 10^{-41} f^4\right) \quad \textbf{(2.6)}$$

```
> plot(20*log10(abs(H_LP_OTA_Pra)),f=0..400e3);
```




```
> evalf(20*log10(abs(subs(f=100e3,H_LP_OTA_Pra))))+6;
```

$$-1.0205999132796280404 \quad (2.7)$$