Elektroakustika

L11B: Reproduktor v dvojkomorovej ozvučnici ako pásmový priepust 4-tého rádu

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http://voice.kemt.fei.tuke.sk

Reproduktor v dvojkomorovej ozvučnici ako pásmový filter 4. rádu

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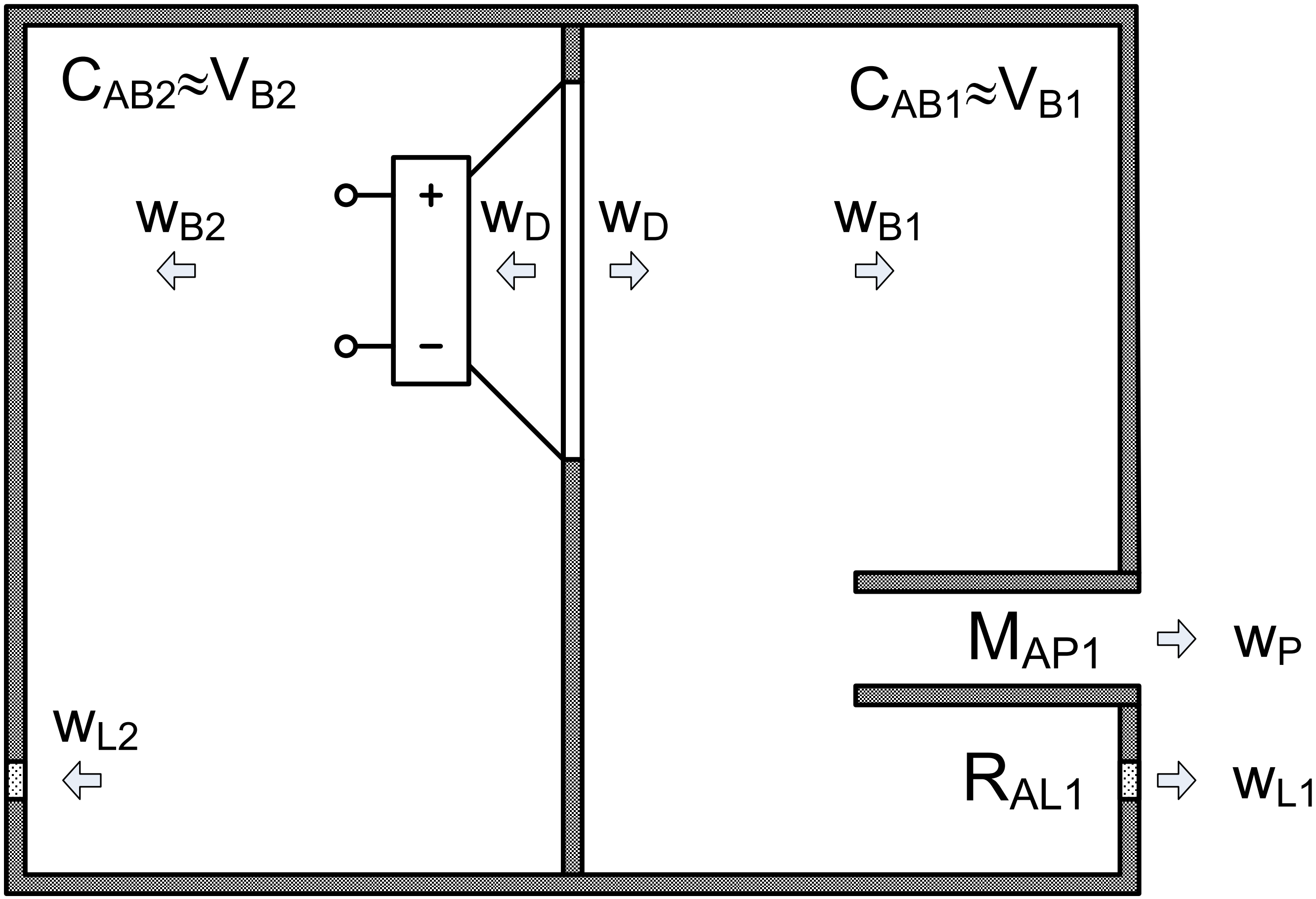
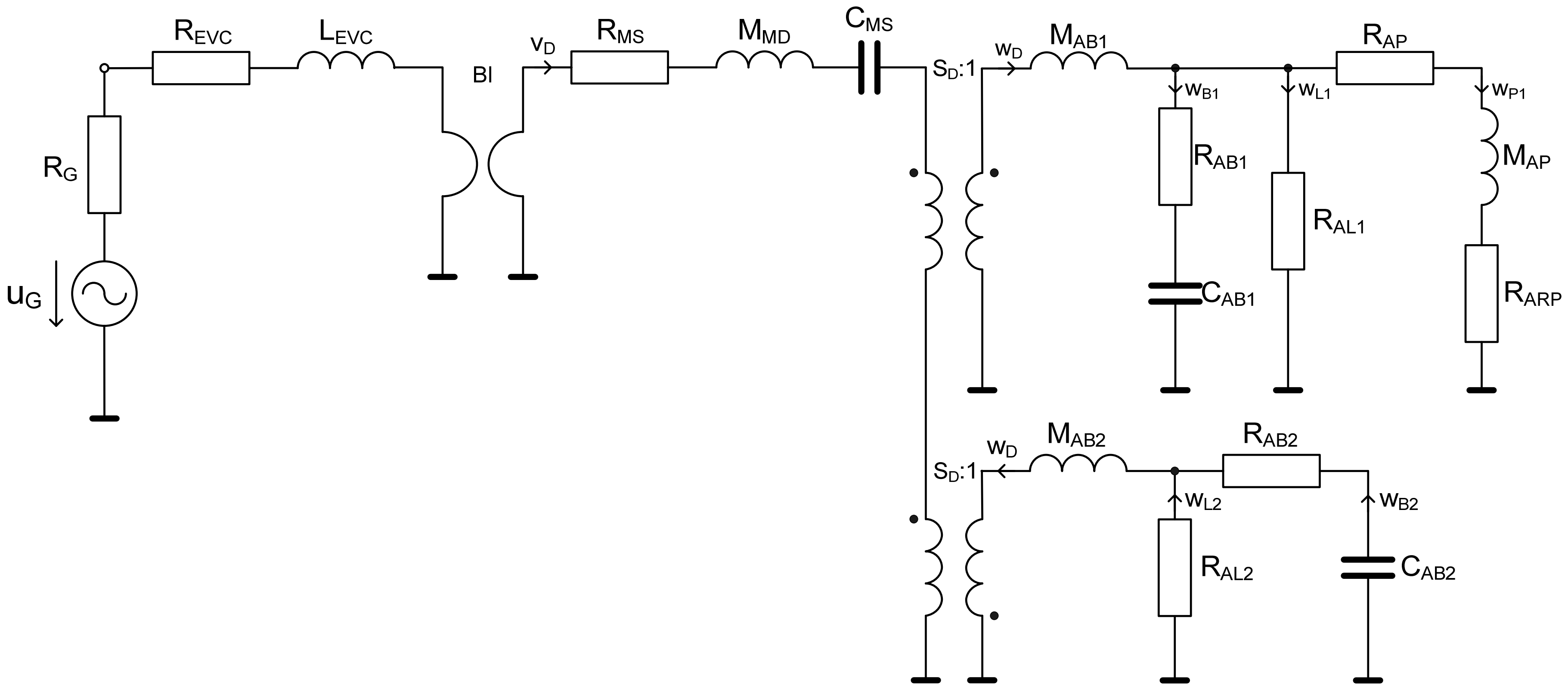


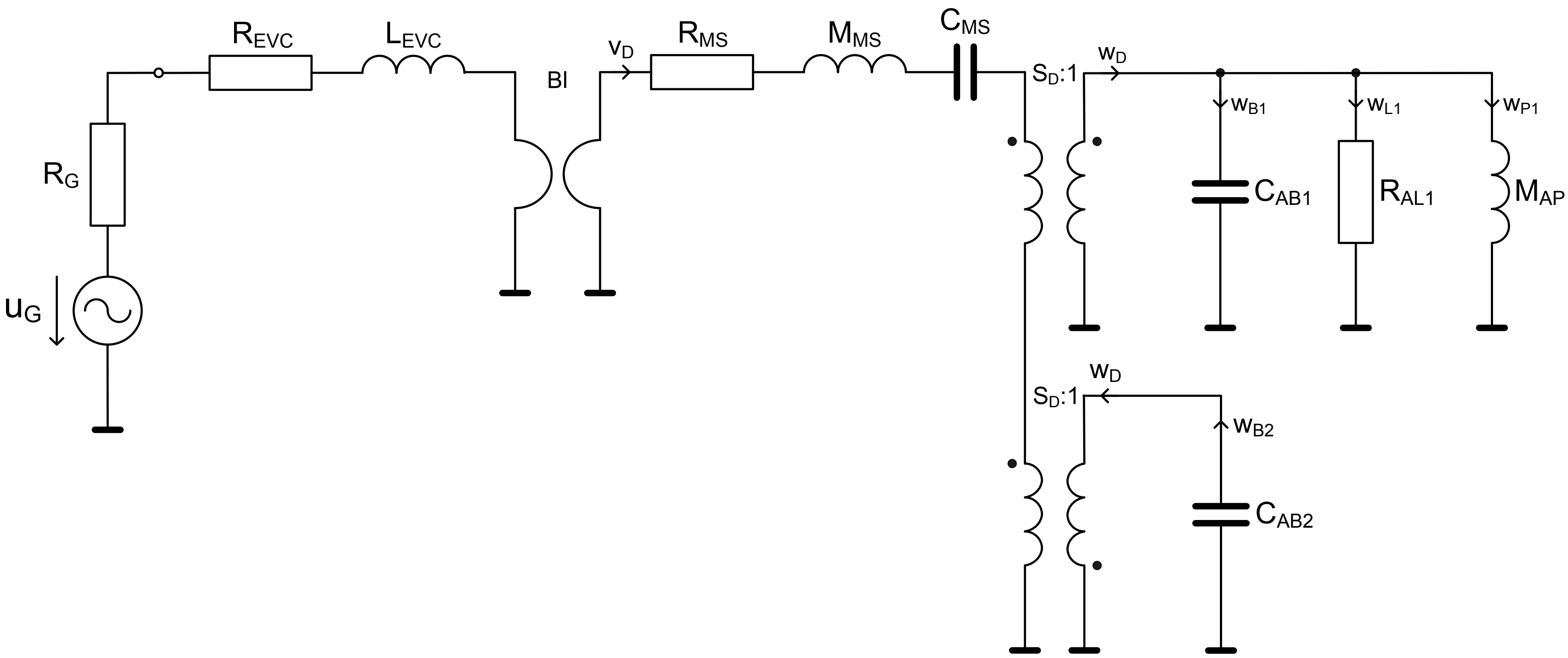
Úplná náhradná schéma



$$R_{ARP} = \dots$$

$$M_{AP} = \frac{\rho_0}{S_P} \cdot \left(l_P + \frac{8 d_P}{3\pi} \right) = \frac{\rho_0}{S_P} \cdot \left(l_P + \frac{4 d_P}{3\pi} \right) + M_{ARP} \quad \Rightarrow \quad M_{ARP} = \frac{\rho_0}{S_P} \cdot \frac{4 d_P}{3\pi}$$

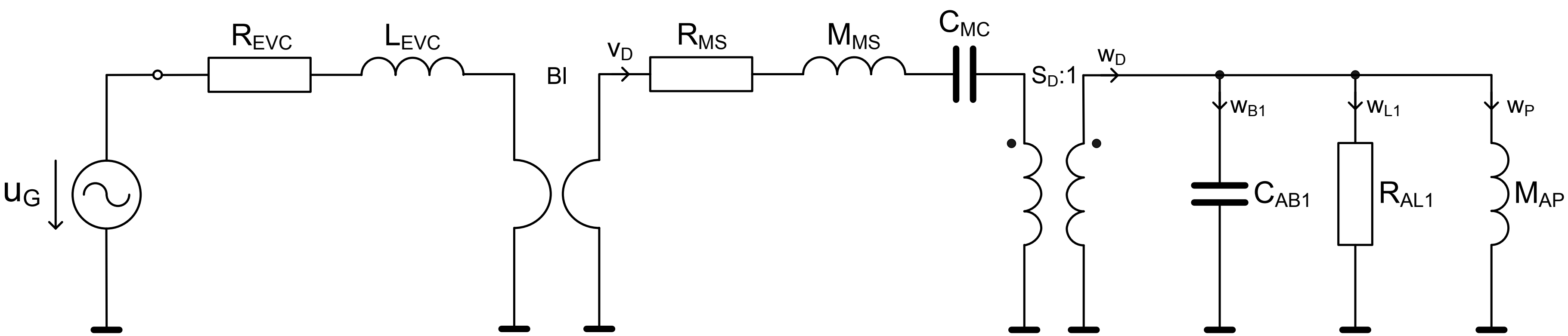
Zjednodušená náhradná schéma



$$M_{ARD} \doteq M_{AB1} \doteq M_{AB2} \quad \Rightarrow \quad M_{MS} = M_{MD} + \left(M_{AB1} + M_{AB2}\right) S_D^{\,2}$$

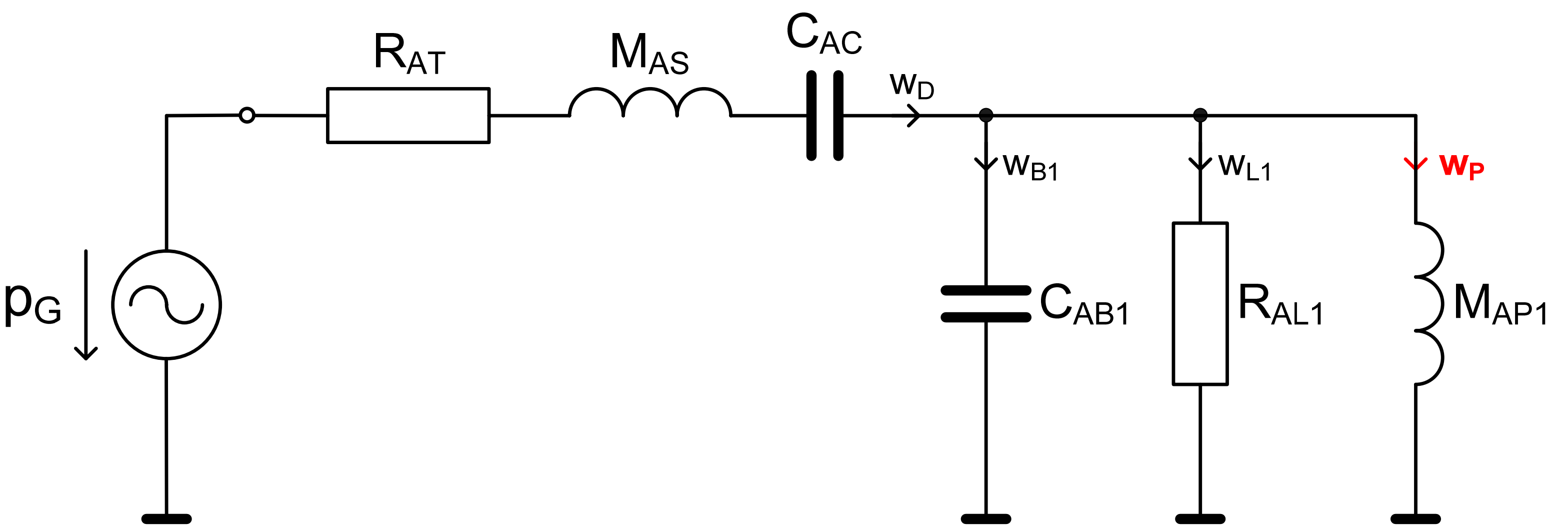
$$R_{AB1} \to 0; \qquad R_{AP} \to 0; \qquad R_{AL2} \to \infty; \qquad R_{ARP} \to 0 \qquad R_{AB2} \to 0$$

Upravená a zjednodušená náhradná schéma sústavy



$$C_{MC} = \frac{C_{MS} \cdot \frac{C_{AB2}}{S_D^{\ 2}}}{C_{MS} + \frac{C_{AB2}}{S_D^{\ 2}}}$$

Akustická analogická schéma sústavy



$$p_G = \frac{U_G \cdot (Bl)}{(R_G + R_{EVC}) \cdot S_D} \qquad R_{AT} = \frac{(Bl)^2}{(R_G + R_{EVC}) \cdot S_D{}^2} + \frac{R_{MS}}{S_D{}^2}$$

$$M_{AS} = \frac{M_{MS}}{S_D{}^2} \qquad C_{AC} = S_D{}^2 \cdot C_{MC}$$

Objemová rýchlosť v akustickom poli sústavy

$$w_P(s) = p_G \cdot \frac{\dfrac{\dfrac{1}{s \cdot M_{AP1}}}{\dfrac{1}{R_{AL1}} + \dfrac{1}{s \cdot M_{AP1}} + s \cdot C_{AB1}}}{R_{AT} + s \cdot M_{AS} + \dfrac{1}{s \cdot C_{AC}} + \dfrac{1}{\dfrac{1}{R_{AL1}} + \dfrac{1}{s \cdot M_{AP1}} + s \cdot C_{AB1}}}$$

Objemová rýchlosť v akustickom poli sústavy

$$w_P(s) = p_G \cdot \frac{sC_{AC}}{\left(s^2 M_{AS} C_{AC} + sC_{AC} R_{AT} + 1\right)\left(s^2 C_{AB1} M_{AP1} + s\, M_{AP1} / R_{AL1} + 1\right) + s^2 C_{AC} M_{AP1}}$$

TS parametre

$$M_{AS}C_{AC} = \frac{1}{\omega_C^{\ 2}} \quad \Rightarrow \quad f_C = \frac{1}{2\pi\sqrt{M_{AS}C_{AC}}}$$

$$M_{AP1}C_{AB1} = \frac{1}{\omega_{B1}^{\ 2}} \quad \Rightarrow \quad f_{B1} = \frac{1}{2\pi\sqrt{M_{AP1}C_{AB1}}}$$

$$\frac{1}{R_{AT}}\sqrt{\frac{M_{AS}}{C_{AC}}} = Q_{TC}$$

$$R_{AL1}\sqrt{\frac{C_{AB1}}{M_{AP1}}} = Q_{L1}$$

Návrhové konštanty

$$\alpha = \frac{C_{AC}}{C_{AB1}} = \frac{\alpha_1}{\alpha_2 + 1} \rightarrow \begin{cases} \alpha_1 = \dfrac{C_{AS}}{C_{AB1}} = \dfrac{V_{AS}}{V_{B1}} \\ \alpha_2 = \dfrac{C_{AS}}{C_{AB2}} = \dfrac{V_{AS}}{V_{B2}} \end{cases}$$

$$h = \frac{\omega_{B1}}{\omega_C} = \frac{h_1}{h_2} \rightarrow \begin{cases} h_1 = \dfrac{\omega_{B1}}{\omega_S} = \dfrac{f_{B1}}{f_S} \\ h_2 = \dfrac{\omega_C}{\omega_S} = \dfrac{f_C}{f_S} \end{cases}$$

Akustický tlak

$$p_0(s) = \frac{\rho_0}{2\pi r} s \cdot w_P(s)$$

$$= \frac{\rho_0}{2\pi r} p_G \frac{s^2 C_{AC}}{\left(s^2 M_{AS} C_{AC} + s C_{AC} R_{AT} + 1\right)\left(s^2 C_{AB1} M_{AP1} + s\, M_{AP1} / R_{AL1} + 1\right) + s^2 C_{AC} M_{AP1}} =$$

$$= \frac{\rho_0}{2\pi r} p_G \frac{1}{M_{AS}} \frac{s^2 \frac{1}{\omega_C{}^2}}{\left(s^2 \frac{1}{\omega_C{}^2} + s \frac{1}{\omega_C} \frac{1}{Q_{TC}} + 1\right)\left(s^2 \frac{1}{\omega_{B1}{}^2} + s \frac{1}{Q_{L1}} \frac{1}{\omega_{B1}} + 1\right) + s^2 \alpha \frac{1}{\omega_{B1}{}^2}} =$$

$$= \frac{\rho_0}{2\pi r} p_G \frac{1}{M_{AS}} \frac{N(s)}{D(s)} = p_m G_{BP4}(s)$$

Prenosová funkcia

$$D(s) = s^4 \frac{1}{\omega_C{}^2} \frac{1}{\omega_{B1}{}^2} + s^3 \left(\frac{1}{\omega_C{}^2} \frac{1}{\omega_{B1}} \frac{1}{Q_{L1}} + \frac{1}{\omega_{B1}{}^2} \frac{1}{\omega_C} \frac{1}{Q_{TC}} \right) +$$

$$+ s^2 \left(\frac{1}{\omega_C{}^2} + \frac{1}{\omega_{B1}{}^2} + \frac{1}{\omega_C} \frac{1}{\omega_{B1}} \frac{1}{Q_{TC}} \frac{1}{Q_{L1}} + \alpha \frac{1}{\omega_{B1}{}^2} \right) + s \left(\frac{1}{Q_{TC}} \frac{1}{\omega_C} + \frac{1}{Q_{L1}} \frac{1}{\omega_{B1}} \right) + 1$$

$$N(s) = s^2 \frac{1}{\omega_C{}^2}$$

Prenosová funkcia

$$\sqrt{\omega_{B1}\omega_C} = \omega_0$$

$$D(s) = s^4 \frac{1}{\omega_0^{\ 4}} + s^3 \frac{1}{\omega_0^{\ 3}} \left(\sqrt{h} \frac{1}{Q_L} + \sqrt{\frac{1}{h}} \frac{1}{Q_{TC}} \right) +$$

$$+ s^2 \frac{1}{\omega_0^{\ 2}} \left(h + \frac{1}{h} + \frac{1}{Q_{TC}} \frac{1}{Q_{L1}} + \alpha \frac{1}{h} \right) + s \frac{1}{\omega_0} \left(\frac{1}{Q_{TC}} \sqrt{h} + \frac{1}{Q_{L1}} \sqrt{\frac{1}{h}} \right) + 1$$

$$N(s) = s^2 \frac{1}{\omega_0^{\ 2}} \left(\frac{\omega_0}{\omega_C} \right)^2$$

Prenosová funkcia: pásmový priepust 4. rádu

$$G_{BP4}(s) = \left(\frac{\omega_0}{\omega_C}\right)^2 \frac{s_0^{\ 2}}{s_0^{\ 4} + a_3 s_0^{\ 3} + a_2 s_0^{\ 2} + a_1 s_0 + 1}$$

Väčšie alebo menšie ako 1 – záleží od celkového nastavenia sústavy

$$a_3 = \frac{\sqrt{h}}{Q_{L1}} + \frac{1}{Q_{TC}\sqrt{h}}$$

$$\sqrt{\omega_{B1}\omega_C} = \omega_0$$

$$a_2 = h + \frac{1}{h} + \frac{1}{Q_{TC}Q_{L1}} + \frac{\alpha}{h}$$

$$s_0 = \frac{s}{\omega_0}$$

$$a_1 = \frac{\sqrt{h}}{Q_{TC}} + \frac{1}{Q_{L1}\sqrt{h}}$$

Transformácia dolného priepustu na pásmový priepust

Dolný priepust :

$$\mathrm{H}_{\mathrm{LP2}} = K\frac{1}{s^2 + s/Q_0 + 1}$$

Substitúcia :

$$s \to B\cdot\left(s_N + \frac{1}{s_N}\right); \quad B = \frac{\omega_N}{\omega_H - \omega_L}; \quad \omega_N = \sqrt{\omega_L \omega_H}; \quad s_N = \frac{s}{\omega_N}$$

Dosadíme :

$$H_{BP4} = \frac{K}{\left[B\cdot\left(s_N + \frac{1}{s_N}\right)\right]^2 + \frac{1}{Q_0}\left[B\cdot\left(s_N + \frac{1}{s_N}\right)\right] + 1} =$$

$$= \frac{K}{B^2}\frac{s_N{}^2}{s_N{}^4 + a_3 s_N{}^3 + a_2 s_N{}^2 + a_1 s_N + 1} \quad \Rightarrow \quad a_1 = a_3 = \frac{1}{Q_0 B}$$

$$a_2 = 2 + \frac{1}{B^2}$$

Šírka pásma a zvlnenie AFCH BPF

$$BW = \frac{f_0}{B}\sqrt{1-\frac{1}{2{Q_0}^2}+\sqrt{\left(1-\frac{1}{2{Q_0}^2}\right)^2+1}}$$

$$Ripple_{dB} = 20\cdot\log_{10}\left[\frac{{Q_0}^2}{\sqrt{{Q_0}^2-0.25}}\right] \quad Q_0 > \frac{1}{\sqrt{2}}$$

...

Porovnaním $H_{BP4}(s)$ a $G_{BP4}(s)$ dostaneme:

$$
\left.
\begin{aligned}
a_1 &= \frac{1}{Q_0 B} &&= \frac{\sqrt{h}}{Q_{TC}} + \frac{1}{Q_{L1}\sqrt{h}} \\
a_2 &= \frac{1}{B^2} + 2 &&= h + \frac{1}{h} + \frac{1}{Q_{TC} Q_{L1}} + \frac{\alpha}{h} \\
a_3 &= \frac{1}{Q_0 B} &&= \frac{\sqrt{h}}{Q_{L1}} + \frac{1}{Q_{TC}\sqrt{h}}
\end{aligned}
\right\}
\begin{aligned}
h &= 1 \\
Q_{TC} &= \left(\frac{1}{Q_0 B} - \frac{1}{Q_{L1}} \right)^{-1} \\
\alpha &= \frac{1}{B^2} + \frac{1}{Q_{L1}} \left(\frac{1}{Q_{L1}} - \frac{1}{Q_0 B} \right)
\end{aligned}
$$

Medzné frekvencie

- …

$$\left.\begin{aligned} B &= \frac{f_0}{f_H - f_L} \\ f_0 &= \sqrt{f_L f_H} \end{aligned}\right\} \Rightarrow f_L{}^2 + \frac{f_0}{B} f_L - f_0{}^2 = 0$$

Riešenie:

$$f_L = f_0\left(\sqrt{\frac{1}{(2B)^2}+1} - \frac{1}{2B}\right)$$

$$f_H = f_0\left(\sqrt{\frac{1}{(2B)^2}+1} + \frac{1}{2B}\right)$$

Činiteľ kvality Q_0 pre zvolenú šírku pásma BW

Z rovníc:

$$BW = \frac{f_0}{B}\sqrt{1-\frac{1}{2Q_0^{\;2}}+\sqrt{\left(1-\frac{1}{2Q_0^{\;2}}\right)^2+1}}$$

$$B = \frac{1}{Q_0}\cdot\frac{Q_{TC}Q_{L1}}{Q_{TC}+Q_{L1}}$$

zostavíme kvadratickú rovnicu v tvare:

$$\left[Q_0^{\;2}\right]^2 + 2A^2\left[Q_0^{\;2}\right] - A^2\left(A^2+1\right) = 0$$

kde:

$$A = \frac{BW}{f_0}\frac{Q_{TC}Q_{L1}}{Q_{TC}+Q_{L1}}$$

Jej riešením je dvojica koreňov, z ktorej vyberieme kladný koreň a dostaneme tak riešenie pre Q_0 v tvare:

$$Q_0 = \sqrt{A\left(\sqrt{2A^2+1}-A\right)}$$

Charakteristická citlivosť sústavy BP4

$$p_0(s)\Big|_{s=j\omega_0} = \underbrace{\frac{\rho_0}{2\pi r}\frac{U_G\cdot(Bl)\cdot S_D}{(R_G+R_{EVC})M_{MS}}}_{\frac{\sqrt{P_E}}{r}\sigma_{(IB)\|1W,1m}} \cdot \underbrace{G_{BP4}(s)\Big|_{s=j\omega_0}}_{\frac{1}{\frac{1}{Q_{TC}Q_{L1}}+\frac{\alpha_1}{\alpha_1+\alpha_2}}=B^2}$$

$$p_0(s)\Big|_{s=j\omega_0} = \frac{\sqrt{P_E}}{r}\sigma_{(IB)\|1W,1m}B^2 = \frac{\sqrt{P_E}}{r}\sigma_{(BP4)\|1W,1m}$$

$$\sigma_{(BP4)\|1W,1m} = \sigma_{(IB)\|1W,1m}B^2$$

Príklad: Návrh ozvučnice pre známy reproduktor a zvolenú šírku pásma

Zvolený reproduktor:

|Seas Prestige CA26RE4X H1316
| Revc=6.1Ohms; Levc=3.08mH; Bl=11.6N/A; Mmd=38.5g; Mmrd=3.8g;
|Rms=1.66Ns/m; Cms=1.1mm/N; Sd=350cm2;
| Fs=25Hz; Qts=0.28; Qms=3.99; Qes=0.30; Vas=164lit.;
|ymax=4mm; sens=91dB; Pe(lt)=80W

Poznáme TS parametre: V_{AS}=164L, f_S =25Hz, Q_{TS}=0.28

Zvolíme: Q_{L1}=10

Zvolíme cieľovú šírku pásma: f_L=25Hz, f_H=150Hz

Vypočítame strednú frekvenciu:

$$f_{B1} = f_C = f_0 = \sqrt{f_L f_H} = \sqrt{25 \cdot 150} = 61.24 \quad [\mathrm{Hz}]$$

Parameter α_2 a V_{B2}:

$$\alpha_2 = \left(\frac{f_0}{f_S}\right)^2 - 1 = \left(\frac{61}{25}\right)^2 - 1 = 5 \quad \Rightarrow \quad V_{B2} = \frac{V_{AS}}{\alpha_2} = \frac{164}{5} = 32.8 \quad [\mathrm{lit}]$$

Parameter Q_{TC}:

$$Q_{TC} = Q_{TS}\sqrt{1+\alpha_2} = 0.28\sqrt{1+5} = 0.69$$

Parameter A:

$$A = \frac{BW}{f_0}\frac{Q_{TC}Q_{L1}}{Q_{TC}+Q_{L1}} = \frac{150-25}{\sqrt{150 \cdot 25}}\frac{0.69 \cdot 10}{0.69+10} = 1.32$$

Parameter Q_0:

$$Q_0 = \sqrt{A\left(\sqrt{2A^2+1}-A\right)} = \sqrt{1.32\left(\sqrt{2 \cdot 1.32^2+1}-1.32\right)} = 1.03$$

Parameter B:

$$B=\frac{f_0}{BW}\sqrt{1-\frac{1}{2Q_0{}^2}+\sqrt{\left(1-\frac{1}{2Q_0{}^2}\right)^2+1}}=\frac{\sqrt{150\cdot 25}}{150-25}\sqrt{1-\frac{1}{2}+\sqrt{\left(1-\frac{1}{2}\right)^2+1}}=0.62$$

Parameter α:

$$\alpha=\frac{1}{B^2}+\frac{1}{Q_{L1}{}^2}-\frac{1}{Q_{L1}}\frac{1}{Q_0\cdot B}=\frac{1}{0.62^2}+\frac{1}{100}-\frac{1}{10}\cdot\frac{1}{1.03}\cdot\frac{1}{0.62}\doteq 2.45$$

Parameter α_1:

$$\alpha_1=\alpha(\alpha_2+1)=2.45(5+1)=14.7 \quad\Rightarrow\quad V_{B1}=\frac{V_{AS}}{\alpha_1}=\frac{164}{14.7}=11.2\quad[\text{lit}]$$

Minimálny priemer BR trubice:

$$D_P\geq\sqrt{f_{B1}\cdot S_D\cdot x_{\max,pp}}=\sqrt{61\cdot 0.035\cdot 0.008}\doteq 13\,[\text{cm}]$$

Dĺžka trubice:

$$L_P=\left(\frac{c_0}{2\pi f_0}\right)^2\frac{S_P}{V_{B1}}-1.463\sqrt{\frac{S_P}{\pi}}=\left(\frac{344}{2\pi\cdot 61}\right)^2\frac{0.0134}{0.0068}-1.463\sqrt{\frac{0.0134}{\pi}}\doteq 91[\text{cm}]$$

Charakteristická citlivosť:

$$\sigma_{(BP4)|1W,1m}=7.9\cdot 10^{-3}\cdot\sqrt{\frac{f_S{}^3 V_{AS}}{Q_{ES}}}\cdot B^2=7.9\cdot 10^{-3}\cdot\sqrt{\frac{25^3\,0.164}{0.30}}\cdot 0.62^2=0.28\,\left[\text{PaW}^{-1/2}\text{m}\right]$$

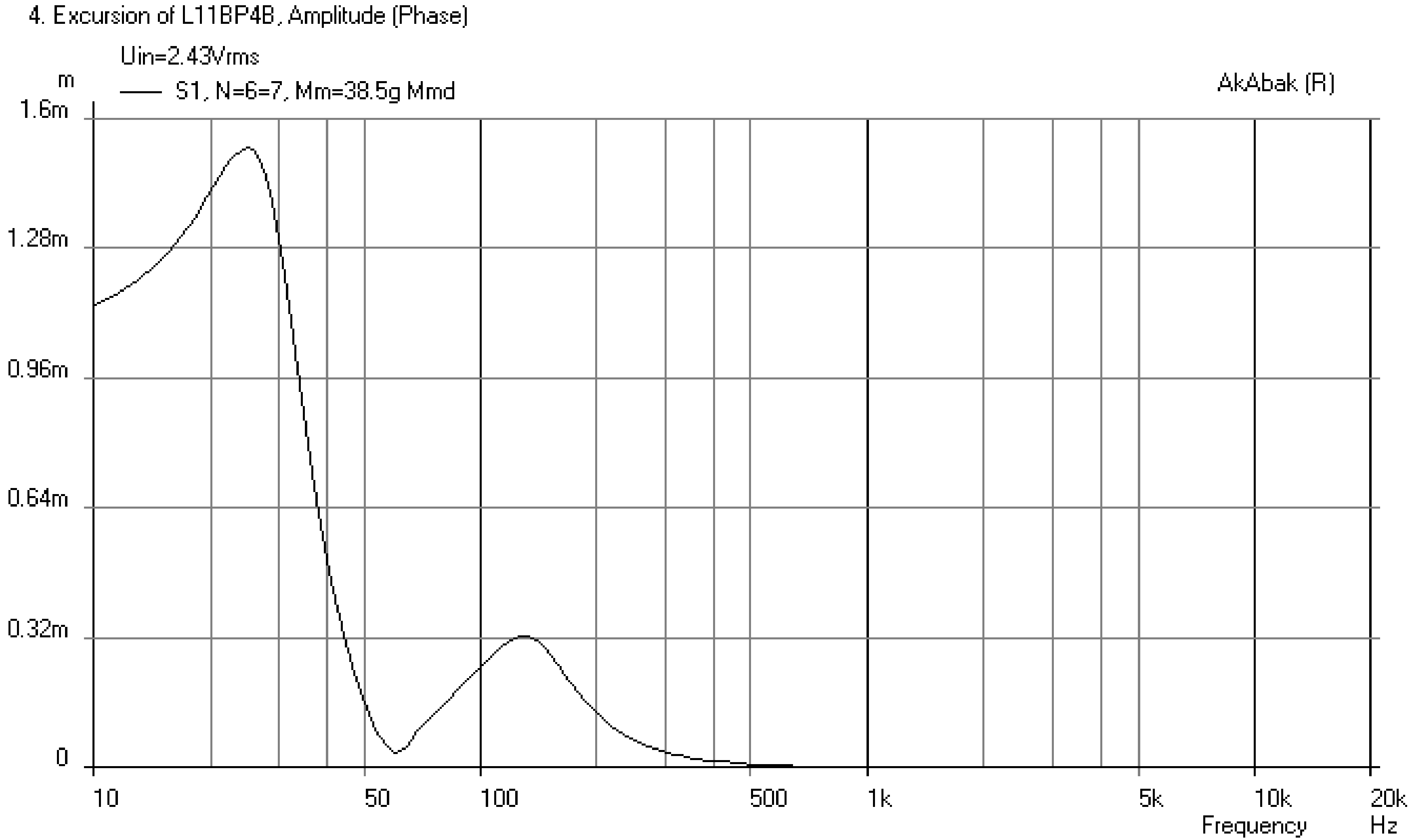
$$L_{\sigma,BP4}=94+20\cdot\log_{10}\sigma_{(BP4)|1W,1m}=94+20\cdot\log_{10}0.28=82.96\,[\text{dB}]$$

Skript na simuláciu sústavy BP4 pomocou „diskrétnej“ náhradnej schémy (S1) a makromodelov Driver a Enclosure

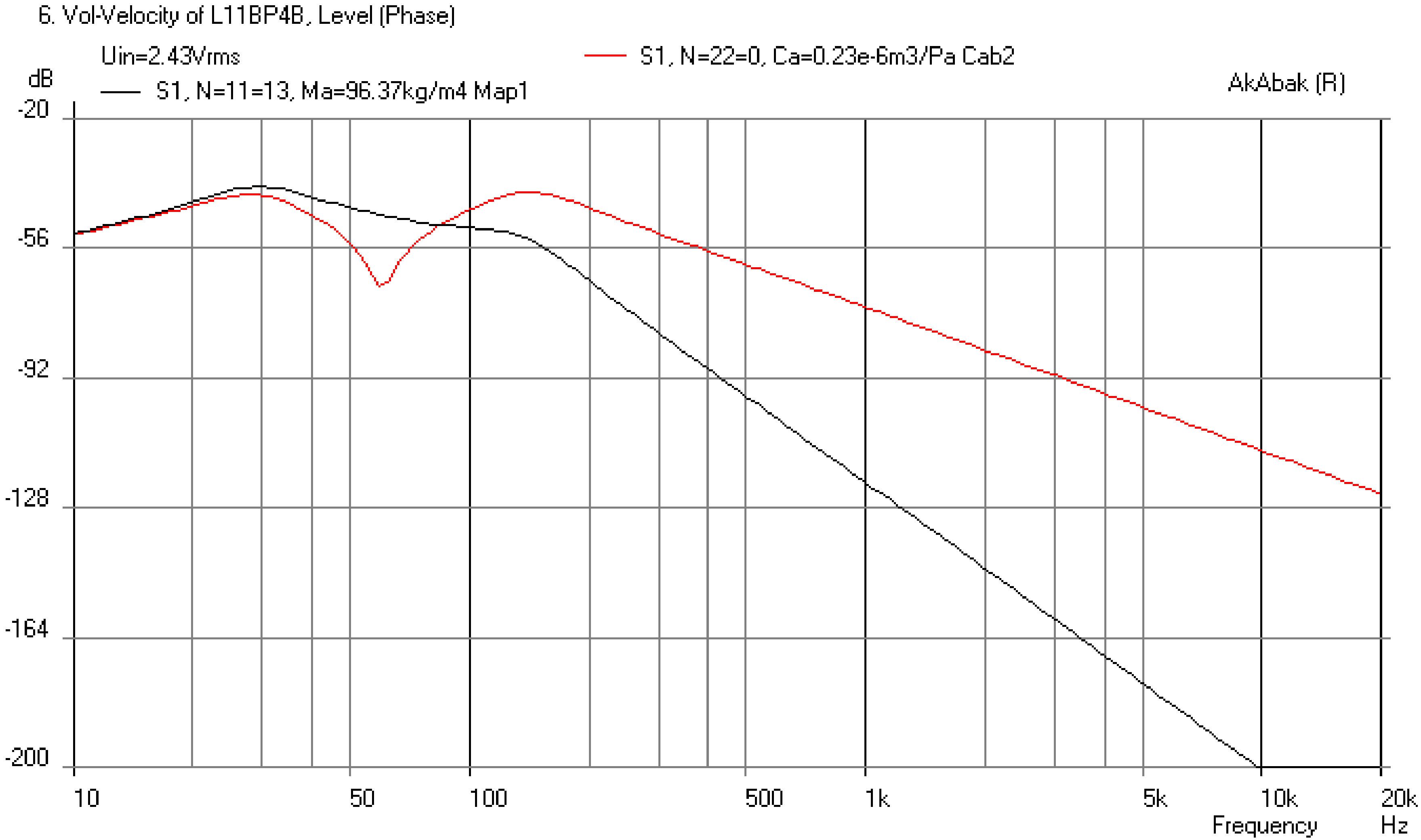
```
| Seas Prestige CA26RE4X H1316
| Revc=6.1Ohms; Levc=3.08mH; Bl=11.6N/A; Mmd=38.5g;
| Mmrd=3.8g; Rms=1.66Ns/m; Cms=1.1mm/N; Sd=350cm2
| Fs=25Hz; Qts=0.28; Qms=3.99; Qes=0.30; Vas=164lit.,
| ymax=4mm; sens=91dB; Pe(lt)=80W

Def_Const
 {roh=1.18; c0=344; Sd=0.035; Rd=sqrt(Sd/pi);
  Mard=(roh*8*Rd)/(3*pi*Sd);
  Vas=0.164; Qts=0.28; Fs=25; xpp=0.008;
  QL1=10; QL2=1000;FL=25;FH=150;BW=FH-FL;
  F0=sqrt(FL*FH);
  alfa2=sqr(F0/Fs)-1;
  VB2=Vas/alfa2;   Cab2=VB2/(roh*c0^2);
  Qtc=Qts*sqrt(1+alfa2);
  A=(BW/F0)*(Qtc*QL1/(Qtc+QL1));
  Q1=sqrt(A*(sqrt(2*A^2+1)-A));
  B=(F0/BW)*sqrt(1-1/2*Q1^2+sqrt(sqr(1-1/2*Q1^2)+1));
  alfa=1/B^2+1/QL1^2+1/(QL1*Q1*B);
  alfa1=alfa*(alfa2+1);
  VB1=Vas/alfa1;
  Cab1=VB1/(roh*c0^2);
  Dp=sqrt(F0*Sd*xpp);Sp=(pi*Dp^2)/4;
  Lp=(c0/(2*pi*F0))*(Sp/VB1)-1.698*sqrt(Sp/pi);
  Map1=1/(sqr(2*pi*F0)*Cab1);
  |Map1=(roh/Sp)*(Lp+(8*Dp)/(3*pi));
  RaL1=QL1*sqrt(Map1/Cab1);RaL2=QL2*sqrt(Mard/Cab2)
 }

Def_Driver  'DRV'
  SD=350cm2  dD1=5.5cm  tD1=6.5cm   |Cone
  fs=25Hz  Vas=164L  Qms=3.99
  Qes=0.3  Re=6.1ohm  Le=3.08mH  ExpoLe=0.618
```

```
System 'S1'
  Resistor   'Rg'  Node=1=2  R=0.001ohm
  Resistor   'Revc'  Node=2=3  R=6.1ohm
  Coil   'Levc'  Node=3=4  L=3.08mH
  Gyrator   'Gy1'  Node=4=0=5=0  Bl=11.6Tm
  MechResistance   'Rms'  Node=5=6  Rm=1.66Ns/m
  MechMass   'Mmd'  Node=6=7  Mm=38.5g
  MechCompliance   'Cms'  Node=7=8  Cm=1.1e-3m/N
  Coupler   'front'  Node=8=9=10
   SD={Sd}   |Piston
  AcouMass   'Mab1'  Node=10=11  Ma={Mard}
  AcouResistance   'Rab1'  Node=11=12  Ra=1Pas/m3
  AcouCompliance   'Cab1'  Node=12=0  Ca={Cab1}
  AcouResistance   'RaL1'  Node=11=0  Ra={RaL1}
  AcouMass   'Map1'  Node=11=13  Ma={Map1}
  Radiator  'Rad1'  Def='front'   Node=13
   x=0  y=0cm  z=0  HAngle=0  VAngle=0
  Coupler   'back'  Node=9=0=0=20
   SD={Sd}   |Piston
  AcouMass  'Mab2'  Node=20=21  Ma={Mard}
  AcouResistance  'Rab2'  Node=21=22  Ra=1Pas/m3
  AcouCompliance  'Cab2'  Node=22=0  Ca={Cab2}
  AcouResistance   'RaL2'  Node=21=0  Ra={RaL2}

System 'S2' |Driver a Enclosure
  Resistor   'Rg'  Node=1=2  R=0.001ohm
  Driver 'D1'  Def='DRV'  Node=2=0=3=4
  Enclosure   'E1'  Node=3
   Vb={VB1}  Sb={Sd}
   fb={F0}  dD={Dp/5}  QD/fo={QL1/F0}  Visc=0
   x=0  y=0  z=0  HAngle=0  VAngle=0
  Enclosure   'E2'  Node=4
   Vb={Vb2}  Sb={Sd}
```

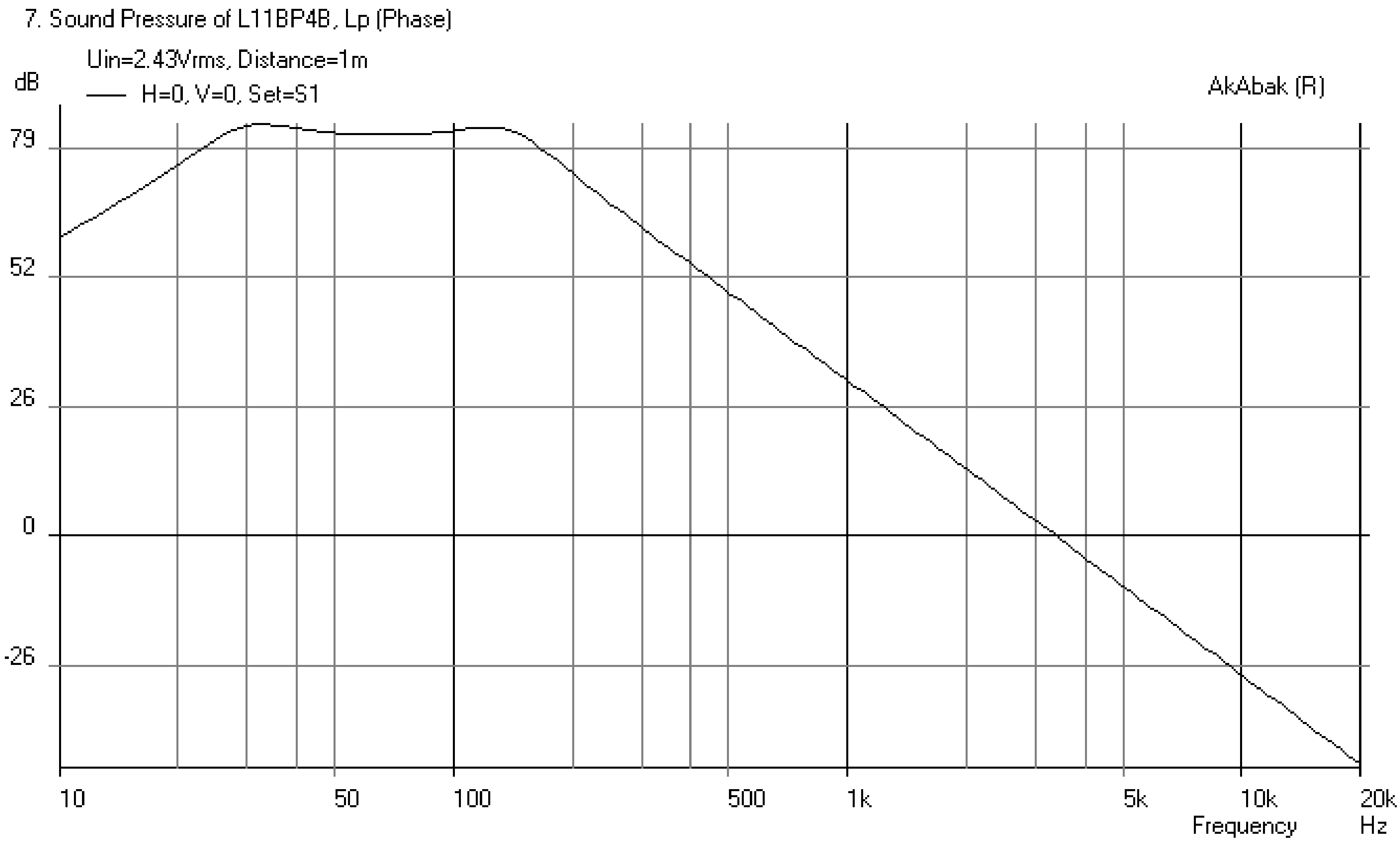
Výchylka reproduktora



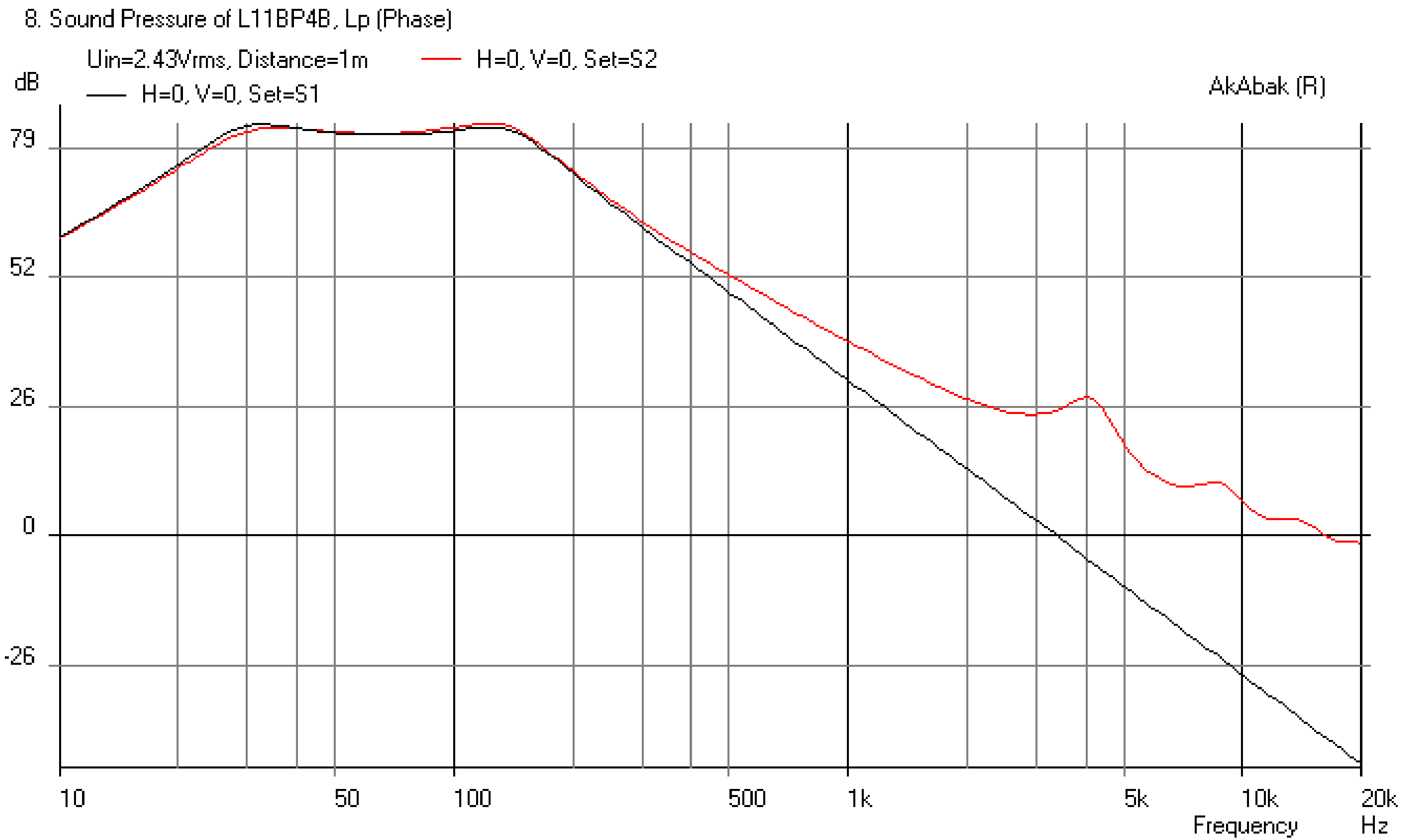
Objemové rýchlosti v trubici a v zatvorenej časti ozvučnice



Akustický tlak sústavy



Akustický tlak sústavy - porovnanie



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