



Elektroakustika

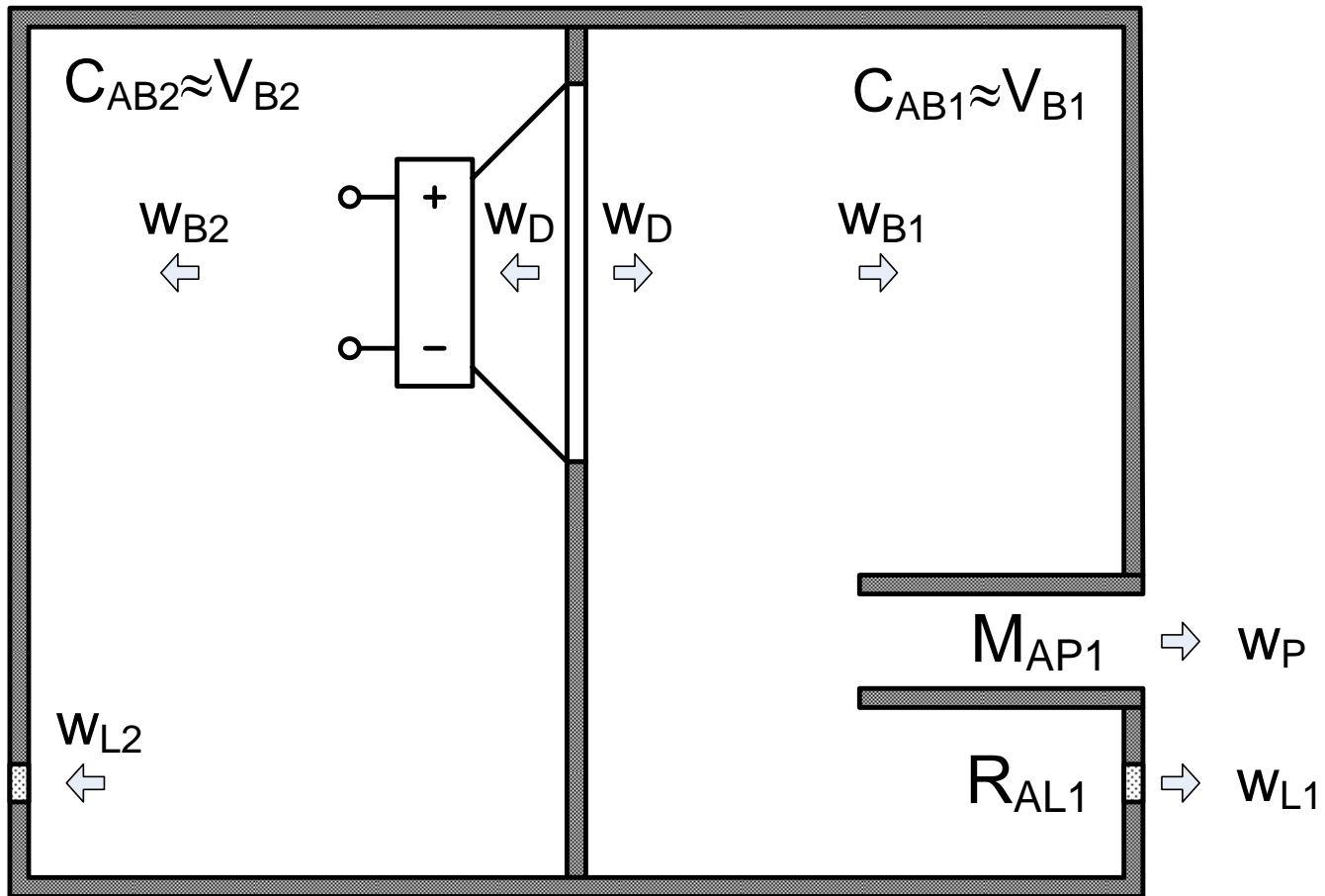
L11B: Reproduktor v dvojkomorovej ozvučnici ako pásmový priepust 4-tého rádu

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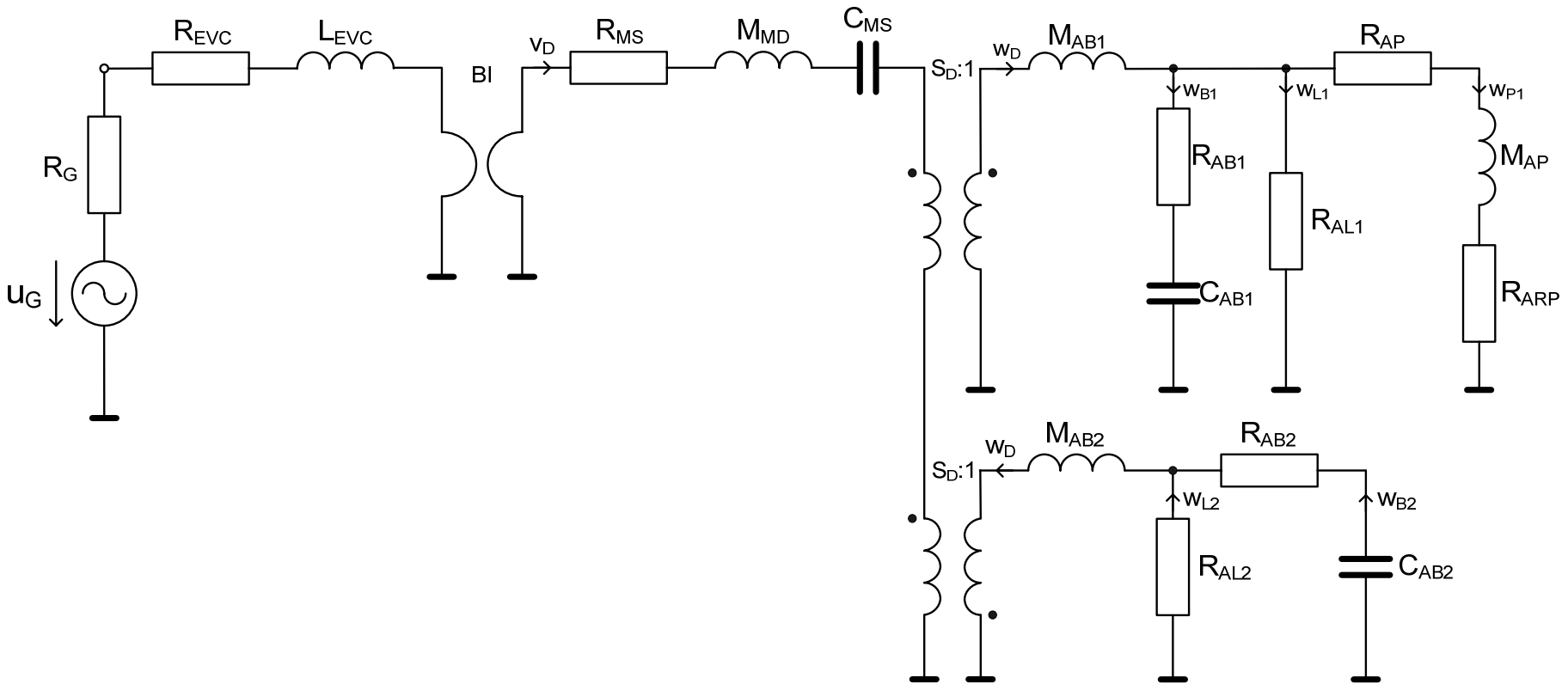
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Reproduktor v dvojkomorovej ozvučnici ako pásmový filter 4. rádu

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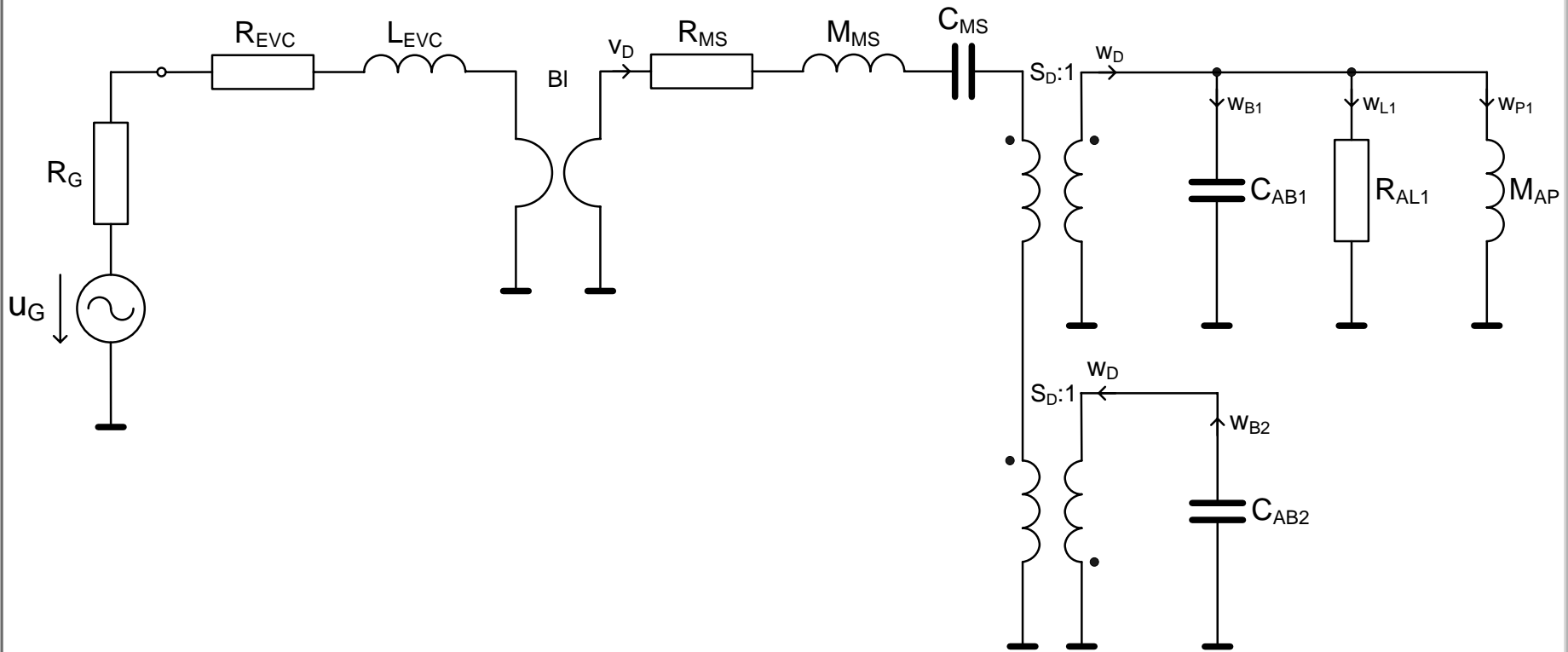
Úplná náhradná schéma



$$R_{ARP} = \dots$$

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

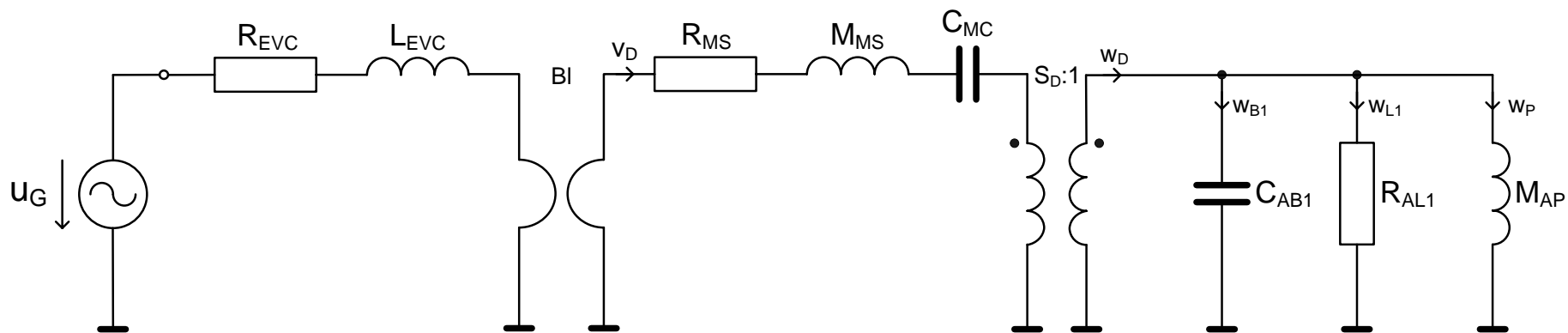
Zjednodušená náhradná schéma



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

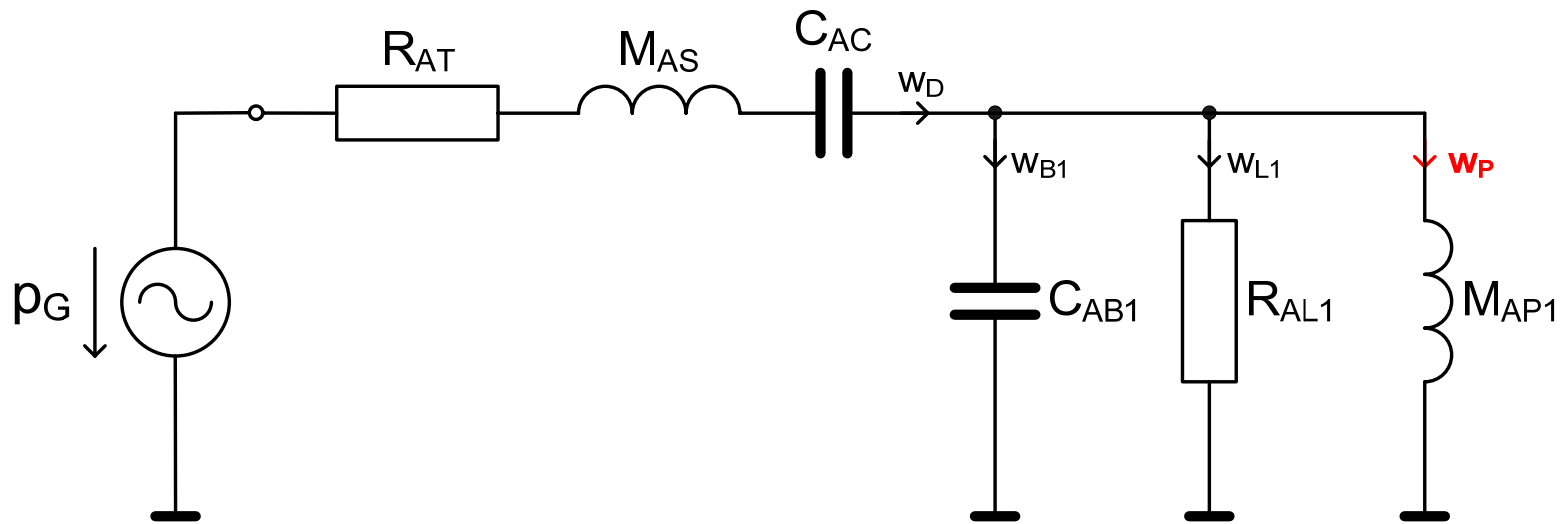
$$R_{AB1} \rightarrow 0; \quad R_{AP} \rightarrow 0; \quad R_{AL2} \rightarrow \infty; \quad R_{ARP} \rightarrow 0 \quad R_{AB2} \rightarrow 0$$

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



$$p_G = \frac{U_G \cdot (Bl)}{(R_G + R_{EVC}) \cdot S_D}$$

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

$$M_{AS} = \frac{M_{MS}}{S_D^2}$$

$$C_{AC} = S_D^2 \cdot C_{MC}$$

Objemová rýchlosť v akustickom poli sústavy

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

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

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

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

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

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

Návrhové konštanty

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

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

Akustický tlak

$$\begin{aligned}
 p_0(s) &= \frac{\rho_0}{2\pi r} s \cdot w_P(s) \\
 &= \frac{\rho_0}{2\pi r} p_G \frac{s^2 C_{AC}}{\left(s^2 M_{AS} C_{AC} + s C_{AC} R_{AT} + 1 \right) \left(s^2 C_{AB1} M_{AP1} + s M_{AP1} / R_{AL1} + 1 \right) + s^2 C_{AC} M_{AP1}} = \\
 &= \frac{\rho_0}{2\pi r} p_G \frac{1}{M_{AS}} \frac{s^2 \frac{1}{\omega_C^2}}{\left(s^2 \frac{1}{\omega_C^2} + s \frac{1}{\omega_C} \frac{1}{Q_{TC}} + 1 \right) \left(s^2 \frac{1}{\omega_{B1}^2} + s \frac{1}{Q_{L1}} \frac{1}{\omega_{B1}} + 1 \right) + s^2 \alpha \frac{1}{\omega_{B1}^2}} = \\
 &= \frac{\rho_0}{2\pi r} p_G \frac{1}{M_{AS}} \frac{N(s)}{D(s)} = p_m G_{BP4}(s)
 \end{aligned}$$

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

$$G_{BP4}(s) = \left(\frac{\omega_0}{\omega_C} \right)^2 \frac{s_0^2}{s_0^4 + a_3 s_0^3 + a_2 s_0^2 + a_1 s_0 + 1} \quad \sqrt{\omega_{B1} \omega_C} = \omega_0 \quad s_0 = \frac{s}{\omega_0}$$

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

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

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

Dolný priepust :

$$H_{LP2} = K \frac{1}{s^2 + s/Q_0 + 1}$$

Substitúcia :

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

Dosadíme :

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

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

Transformácia dolného priepustu na pásmový priepust

Šírka pásma a zvlnenie AFCH BPF

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

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

...

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

• ...

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

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:

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

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 citlivost' sústavy BP4

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

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

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

Príklad:

Návrh ozvučnice pre známy reproduktor a zvolenú šírku pásma

Zvolený reproduktor:

|Seas Prestige CA26RE4X H1316

| $R_{vc}=6.1\text{Ohms}$; $L_{vc}=3.08\text{mH}$; $Bl=11.6\text{N/A}$; $M_{md}=38.5\text{g}$; $M_{mrd}=3.8\text{g}$;

| $R_{ms}=1.66\text{Ns/m}$; $C_{ms}=1.1\text{mm/N}$; $S_d=350\text{cm}^2$;

| $F_s=25\text{Hz}$; $Q_{ts}=0.28$; $Q_{ms}=3.99$; $Q_{es}=0.30$; $V_{as}=164\text{lit.}$;

| $y_{max}=4\text{mm}$; $sens=91\text{dB}$; $P_{e(lt)}=80\text{W}$

Poznáme TS parametre:

$$V_{AS}=164L, f_S=25\text{Hz}, Q_{TS}=0.28$$

Zvolíme:

$$Q_{L1}=10$$

Zvolíme cieľovú šírku pásma:

$$f_L=25\text{Hz}, f_H=150\text{Hz}$$

Vypočítame strednú frekvenciu:

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

Parameter α_2 a V_{B2} :

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

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 :

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

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:

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

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

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'

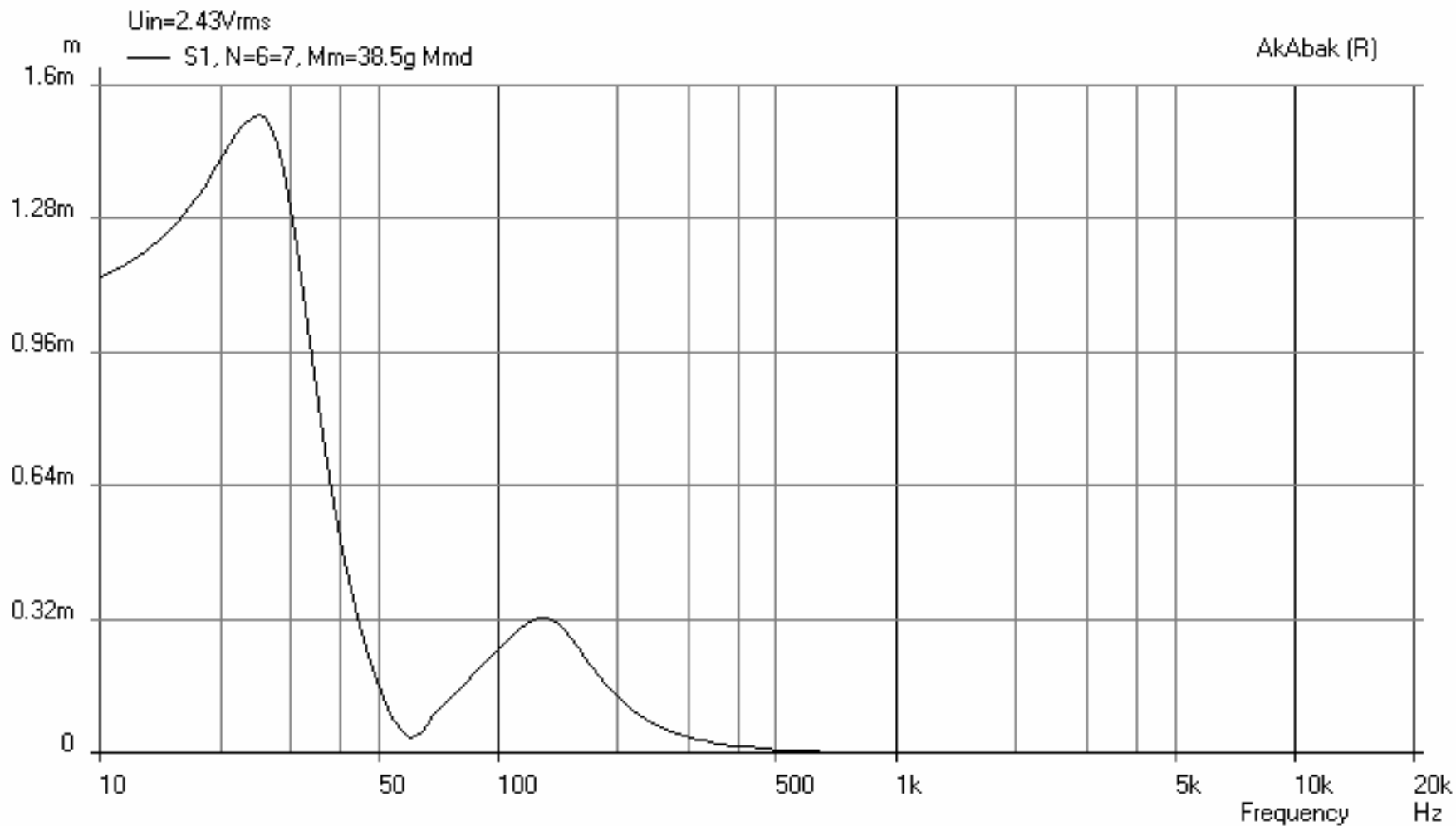
```
Resistor 'Rg' Node=1=2 R=0.001ohm  
Resistor 'Revc' Node=2=3 R=6.1ohm  
Coil 'Levc' Node=3=4 L=3.08mH  
Gyrator 'Gy1' Node=4=0=5=0 Bl=11.6Tm  
MechResistance 'Rms' Node=5=6 Rm=1.66Ns/m  
MechMass 'Mmd' Node=6=7 Mm=38.5g  
MechCompliance 'Cms' Node=7=8 Cm=1.1e-3m/N  
Coupler 'front' Node=8=9=10  
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

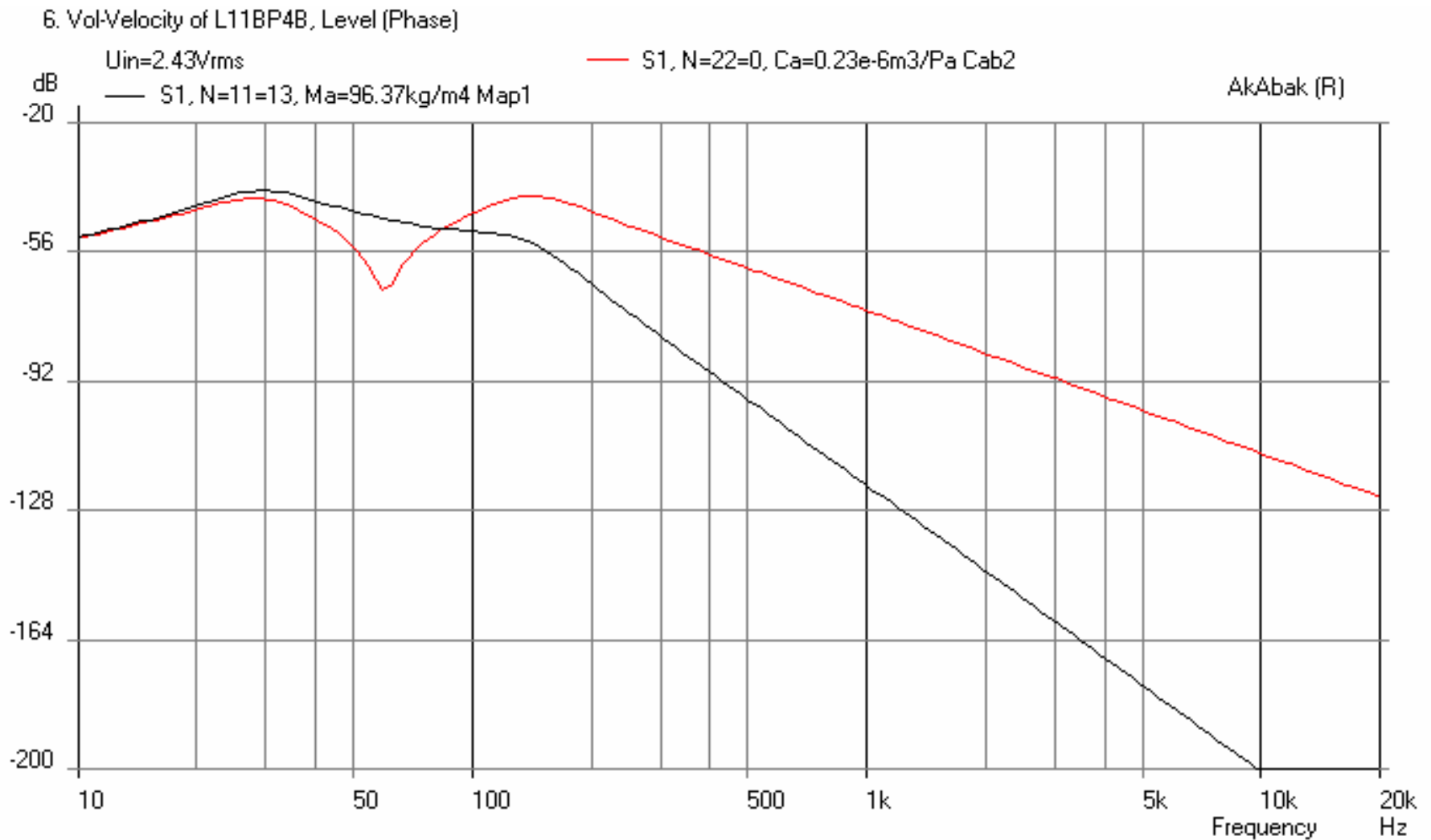
```
Resistor 'Rg' Node=1=2 R=0.001ohm  
Driver 'D1' Def='DRV' Node=2=0=3=4  
Enclosure 'E1' Node=3  
Vb={VB1} Sb={Sd}  
fb={F0} dD={Dp/5} QD/fo={QL1/F0} Visc=0  
x=0 y=0 z=0 HAngle=0 VAngle=0  
Enclosure 'E2' Node=4  
Vb={VB2} Sb={Sd}
```


Výchylka reproduktora

4. Excursion of L11BP4B, Amplitude (Phase)

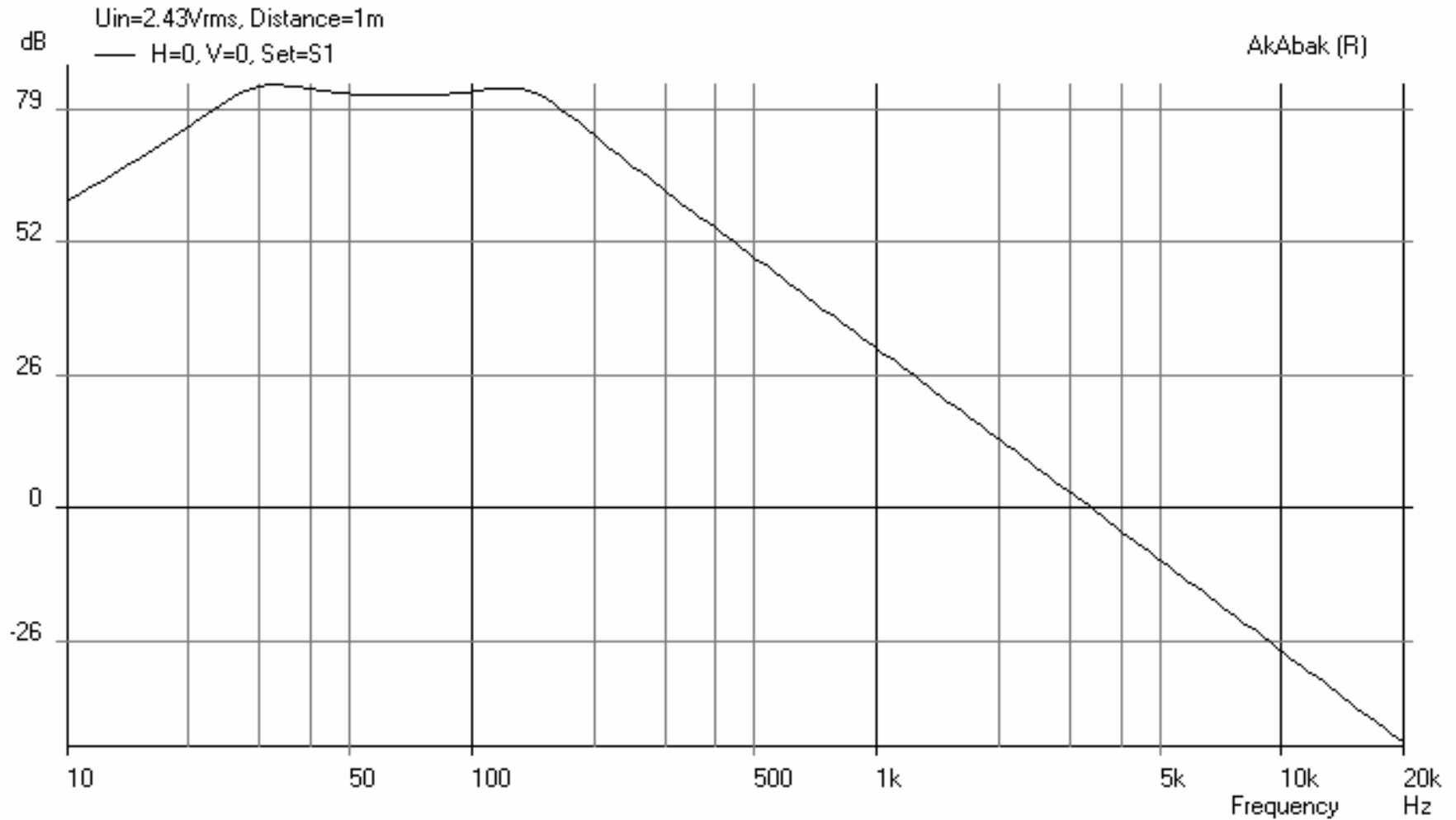


Objemové rychlosti v trubici a v zatvorenej časti ozvučnice



Akustický tlak sústavy

7. Sound Pressure of L11BP4B, Lp (Phase)



Akustický tlak sústavy - porovnanie

8. Sound Pressure of L11BP4B, Lp (Phase)

